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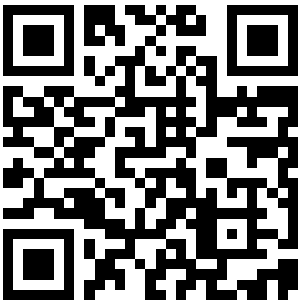

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AVIONICS INERTIAL AND RADAR NAVIGATION SYSTEMS SPECIALIST

(AFSC 32854)

Volume 4

Inertial Navigation Systems

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Preface

IN THE PREVIOUS volume, the problems of navigation and the steps involved in solving them were presented.

In this volume, we present the principles, characteristics, and of an inertial navigation system (INS). We used a typical INS to present a block diagram analysis plus a circuit analysis of the assemblies. The system presented in this volume solves the navigational problems discussed in Volume 3.

Foldouts 1 through 31 are oversized schematics printed and bound as a separate inclosure to this volume. Whenever you are referred to one of these foldouts, please turn to the separate inclosure to locate it.

This volume is valued at 36 hours (12 points).

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Principles of Inertial Navigation

WHEN NAVIGATING, if you know precisely your point of departure and the speed and direction in which you are traveling, you should be able to determine at any instant your position with respect to your starting point. However, whether you are navigating on land, on the sea, or in the air, a complexity of factors invariably enters that prevents you from maintaining the desired and—what is more important—a *known* speed and heading. For this reason, regardless of your mode of travel, you must depend on varying degrees of external checkpoints.

The checkpoints you use when traveling by auto, for example, are road signs. When traveling by air, if the visibility is good, you can check your position from time to time by looking for recognizable landmarks, such as rivers, cities, railroad tracks, and water towers. But what if the visibility is not good? Although you can use radio navigation aids, even these aids have their limitations. UHF beacons are limited by the earth's horizon to a distance along the line of sight. Lower frequency radio stations or beacons are effective over greater distances, but these are subject to both natural (static) and human (jamming) interference. Under certain conditions, you can determine your position by taking a fix on a star. But if you can see, you can be seen—and this, if you're involved in certain military operations, is not good. It is evident then, that a more desirable navigation system is required.

Inertial navigation is that system. It plays just such an important part in the Air Force mission. Successful completion of the mission hinges upon the operation of the equipment and thus upon the proficiency of assigned maintenance personnel. The purpose of this volume is to help you become more knowledgeable of the inertial navigation system, which is part of your Air Force specialty.

1-1. Introduction to Inertial Guidance

The inertial navigation system is a navigation system that is (1) entirely free from external checkpoints, (2) capable of operating over a large area of the earth's surface, (3) capable of navigating at high and low altitudes, (4) jamproof, (5) secure (i.e., nonradiating), and (6) able to maintain its orientation during all aircraft maneuvers.

One way of classifying an INS is by the type of reference it uses. In this section, we are going to introduce you to the type you will find most common in your career field.

600. Differentiate between characteristics of inertial guidance systems.

Inertial Guidance Systems. *Inertial guidance* is the art of directing a moving object from one place to another by means of an inertial system. An inertial system is one that derives basic navigation information from accelerometers and gyroscopes. These are inertial sensing devices whose principles of operation will be explained.

An inertial guidance system may be completely self-contained (a pure inertial navigator) or it may be used in conjunction with other navigation devices (a hybrid system). Whether the inertial system be a pure or hybrid system, it can be further classified as *analytic* or *semianalytic*. The *analytic* system is oriented to inertial space and is normally used on space vehicles. The *semianalytic* system is oriented to the local vertical, and may be used in either a slow manned aircraft with long endurance or in a high-performance manned aircraft with long range. Because you will deal more with the latter, we selected the semianalytic system for discussion in this volume.

In the semianalytic inertial system, the gyroscopes (instruments that sense angular displacement or angular velocity) and the accelerometers (instruments that sense any change of motion or velocity of a vehicle) are, as we said, oriented to the local vertical. The local vertical is an imaginary line, perpendicular to the surface of the earth, that passes through both the vehicle and the center of the earth. In the analytic inertial system, the

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gyroscopes and accelerometers are oriented to inertial space.

Exercises (600):

Place an A or an S to the left of each of the following to indicate a characteristic of analytic or semianalytic.

___ 1. Oriented to local vertical.
___ 2. Oriented to inertial space.
___ 3. Used on space vehicles.
___ 4. Used on long-endurance or long-range aircraft.

601. Name the axes required by a semianalytic inertial guidance system frame of reference and information obtained from the frame of reference.

Semianalytic Inertial Guidance System. For the semianalytic inertial system to operate properly, it must establish and faithfully maintain a frame of reference. This frame of reference is formed by three mutually perpendicular coordinate axes. These axes are defined as the *east-west*, *north-south*, and *vertical* axes. Using this frame of reference, we obtain pitch, roll, and azimuth information. Using this information plus velocity furnished by the accelerometers, the computer determines instantaneous position, ground-track velocity, and/or bearing and range to a known destination. All of the above signals are available for use by associated avionics equipment. Later in this volume, the tie-in of the inertial navigation system with associated avionics equipment will be explained.

Exercises (601):

1. The semianalytic inertial guidance system frame of reference requires how many axes? Name the axes.

2. What information is obtained from a semianalytic frame of reference?

602. Complete sentences concerning components and corrections associated with a semianalytic frame of reference.

Frame of Reference for a Semianalytic System. When we use the local vertical as a reference, inertial navigation is essentially a problem of establishing a frame of reference and sensing motion within it. This frame of reference is derived in the following manner:

a. By moving a space reference at a predetermined rate to compensate for the rotation of the earth (earth rate) and the movement of the vehicle over the surface of the earth (vehicle rate) to define an earth reference in a plane parallel to the surface of the earth.

b. By establishing and maintaining a known direction or heading reference within the earth reference.

Earlier, we stated that the frame of reference is defined by three reference axes, an east-west axis, a north-south axis, and a vertical axis. These axes are usually designated by letters X, Y, and Z respectively. Therefore, vehicle acceleration, velocity, and instantaneous positions are described in respect to these axes, or as X, Y, and Z components.

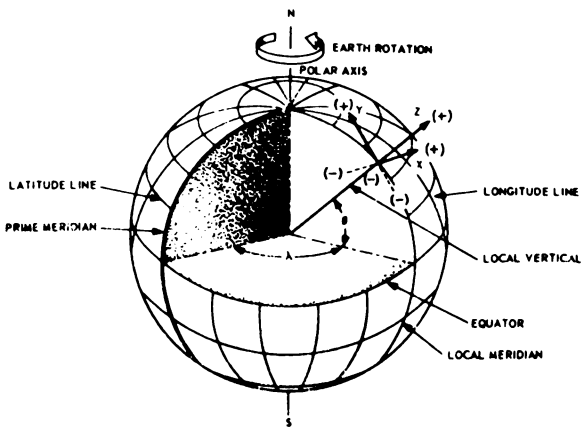

Figure 1-1. Conventional latitude-longitude coordinate system.

Figure 1-1 illustrates a conventional latitude-longitude coordinate system employed by the semianalytic inertial navigation system. The angle between the geographic vertical and the plane of the Equator (latitude) is designated phi ϕ. The angle between the projection of the geographic vertical on the plane of the Equator and the prime meridian (Longitude) is designated lambda λ. The Z-axis is coincident with the local vertical and positive away from the

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center of the earth. The Y-axis is perpendicular to the Z-axis, parallel to the plane of the local meridian, and positive directed north. The X-axis is perpendicular to both the Y- and Z-axes and positive directed east.

Accelerometers are so constructed that they have only one sensitive axis. When an accelerometer is mounted with its sensitive axis along an axis of the frame of reference, it senses the total acceleration of the vehicle along that axis. However, the acceleration it senses is in respect to inertial space. It does not sense the true acceleration because coriolis and centripetal accelerations are included. Coriolis acceleration is the result of a deflecting force exerted by the rotation of the earth upon any object in motion, diverting it to the right of velocity in the Northern Hemisphere and to the left in the Southern Hemisphere. Centripetal acceleration is caused by centripetal force, which is defined as the drawing of a body toward the center around which it revolves. To resolve true acceleration, corrections for coriolis and centripetal are necessary. How we arrive at these corrections will be explained in detail later in this volume.

Exercises (602):

1. The east-west axis is designated as the____ axis and positive directed _____.
2. The north-south axis is designated as the___ axis and positive directed_____.
3. The vertical axis is designated as the _____ axis and positive directed_____.
4. Corrections for_____acceleration and _____ acceleration is necessary in a semianalytic inertial system in order to sense true acceleration.
5. The_____ -axis is coincident with the local vertical.
6. The angle between the geographic vertical and the plane of the Equator (ϕ) is called _____ _____.

1-2. Inertial Navigation Problems and Solutions

In Volume 3 of this CDC, the navigation problems and their solutions were presented. The inertial navigation system you will study in this volume automatically solves the navigation problems of ground track velocity, instantaneous position, attitude, and bearing and range to a desired destination. It is necessary that you understand the problems and solutions of (1) determining velocity, (2) determining distance from velocity, (3) determining distance from acceleration, and (4) resolving acceleration. Therefore, the remainder of this chapter is devoted to a general discussion of these problems and their solutions.

603. Define velocity and acceleration; also state the method for converting one to the other.

Determining Velocity. The main advantage of an inertial guidance system is its ability to determine, without an external reference, the velocity of a vehicle and the distance it has traveled. That is, you do not have to use radar or radio navigation aids to define the vehicle velocity and position. The accelerometer senses any change of acceleration of a vehicle, and from this sensing are computed velocity and position. In order for you to fully understand these computations, we discuss some of the basic methods used in obtaining velocity.

With an automobile, the problem of measuring speed and distance covered is relatively simple. Each revolution of the wheels corresponds to a definite forward movement, with the amount of movement being dependent upon the size of the tires. Since the rate at which the automobile moves forward is directly related to the number of revolutions the wheels make per hour, you can easily obtain indications of both the speed and the distance covered with the passing of time.

The task of measuring the speed of an automobile is easy because the tires are in continuous contact with the ground. Since an aircraft in flight cannot conveniently have contact with the ground, its speed with respect to the ground cannot be measured directly. You can calculate the groundspeed of an aircraft by using airspeed and forecast windspeed and direction (Vw), as explained in Volume 3, but all three of these factors are variables. By using acceleration to determine velocity, you reduce the number of variables and thus increase your accuracy. Let us see how velocity can be determined from acceleration.

According to Sir Isaac Newton, a body at rest or in uniform motion tends to remain at rest or in uniform motion indefinitely unless it is subjected to a force. When acted upon by a force, the body experiences an acceleration. The relation between the force and acceleration is given by the expression $F = MA$, where F is the force, A is the acceleration, and M is the mass of the body.

The acceleration experienced by the body causes its velocity to change. Thus, if the body was formerly at rest, it now moves with a velocity that continues to increase as long as the force is applied. If the body was formerly in uniform motion, its velocity begins to change as long as the force is applied. The rate at which the velocity of a body changes when subjected to an external force, is a function of

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acceleration—the greater the acceleration, the greater the rate of change of velocity.

The relationship between acceleration and velocity is very similar to the relationship between velocity and distance. *Velocity is rate of change of distance, and acceleration is rate of change of velocity.* If the acceleration of a body is known, its velocity can be computed by integrating the acceleration with respect to time. Conversely, if the velocity of the body is known, its acceleration can be computed by differentiating (taking the first derivative of) the velocity. Differentiation and integration are inverse mathematical processes. If we know the rate at which a quantity is changing at a given instance and we want to know what the quantity is at that instance, we integrate. If, on the other hand, we know what the quantity is at any instance and would like to know the rate at which the quantity is changing, we differentiate.

Exercises (603):

1. Define velocity and acceleration.

2. If the acceleration of an object is known, how can you determine velocity?

3. If the velocity of an object is known, how can you compute its acceleration?

604. Specify whether given statements about the simple system that inertial navigation utilizes to determine distance are true or false, and correct the false statements.

Determining Distance. We explained above that the relationship between distance and velocity is similar to that existing between velocity and acceleration. If velocity can be computed by integrating acceleration, why not integrate velocity to obtain distance? This is precisely what is done—acceleration is integrated to obtain velocity, and velocity in turn is integrated to obtain distance.

A device capable of sensing and measuring acceleration is called an *accelerometer.* The easiest way to visualize an accelerometer is to think of a brass block resting on a frictionless slide. Imagine further that the block is tied to one end of the slide by means of a spring, as shown in figure 1-2. Accelerate the slide in the direction indicated, and the block experiences a force that causes it to move until the tension in the restraining spring is equal to the force causing the acceleration. The distance the block moves against the restraining force of the spring varies directly with the acceleration imparted to the block. Hence, by mounting a pickoff between the block and the slide, you can easily measure the acceleration experienced by the block.

Because the accelerometer is an inertial device, it matters not whether the transporting vehicle be an automobile, an airplane, or a submarine, etc. If the vehicle undergoes a change in velocity along the sensitive axis of the accelerometer, the accelerometer registers the change. Accelerometers may be designed to measure linear acceleration or angular acceleration. Those used in inertial navation systems are linear; that is, they detect acceleration only along a straight line. Accelerometers must be extremely sensitive over a wide range of acceleration.

By using either electrical or mechanical devices, acceleration can be converted into distance in a number of ways. An electrical system is shown in figure 1-3. Suppose the speed of motor 1 is made proportional to acceleration. This can be done by letting the motor be a variable speed motor whose speed is controlled by the output of the accelerometer. Rev/min of the motor is then proportional to ft/sec/sec. At the end of a given period of time, the motor will have turned through a certain number of revolutions, depending upon the instantaneous values of voltages from the accelerometer. The total shaft rotation is then the integral of the accelerometer output. This means that the total angle of rotation of the shaft is a measure of the linear velocity of the vehicle upon which the accelerometer is mounted. Suppose that motor 1 drives a multiturn potentiometer whose output voltage is proportional to the total angle through which the shaft has turned. This voltage is a measure of the linear velocity of the vehicle. Let us feed this voltage to a second variable speed motor. The speed of the second motor is proportional to the linear velocity of the vehicle upon which the accelerometer is mounted. The total shaft rotation of the second motor is proportional to the integral of velocity. Therefore, the total

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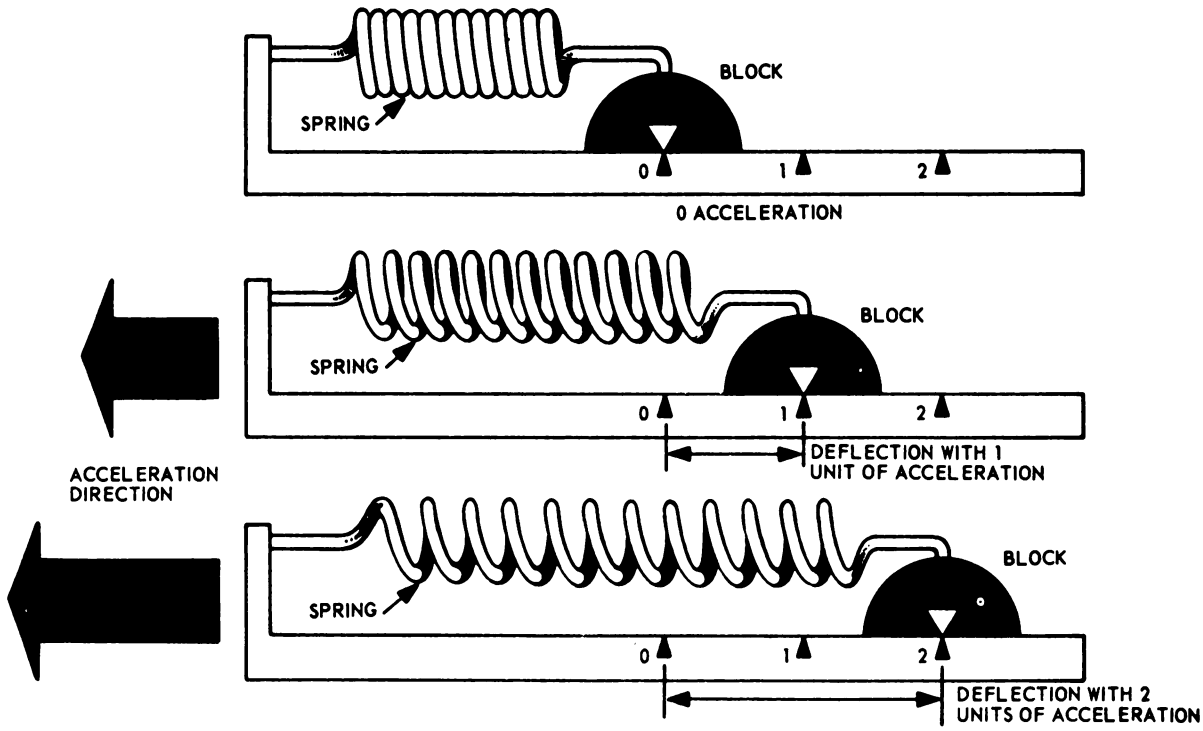

Figure 1-2. Simple accelerometer.

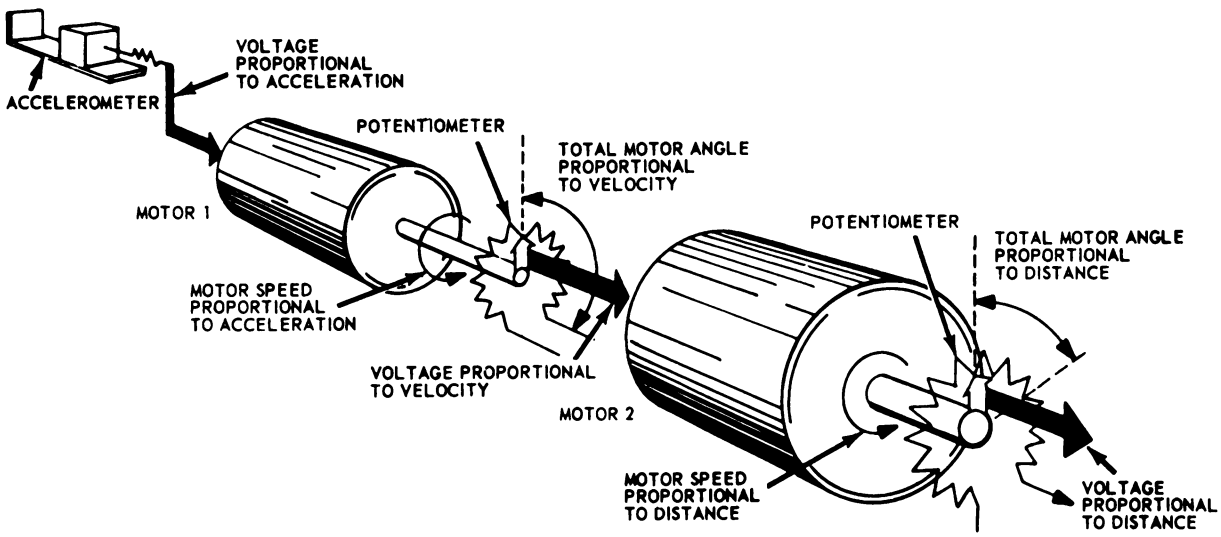

Figure 1-3. Deriving distance from accelerometer.

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shaft rotation of the second motor is proportional to the linear distance covered by the vehicle upon which the accelerometer is mounted. If the second motor is made to drive another potentiometer similar to the first one described, a voltage can be obtained that is a direct measure of the linear distance traveled by the vehicle. Since the output of the second potentiometer is proportional to distance traveled, it can be made to deflect the pointer of an instrument calibrated in miles. Study this paragraph again.

When the vehicle upon which the accelerometer is mounted reaches the desired speed and continues to move at a constant speed, the acceleration becomes zero, the accelerometer output becomes zero, and motor 1 stops. The arm of the first potentiometer remains stationary and continues to feed a voltage that is representative of the velocity of the moving vehicle to the second motor. With a constant input, motor 2 continues to turn; and as it does so, it continues to drive the second potentiometer so that the distance it represents may increase uniformly with the passing of time.

Exercises (604):

Identify the following statements as true or false; if a statement is false, correct it.

___ 1. Accelerometers are devices used to measure acceleration caused by a force applied to the vehicle.

___ 2. The accelerometer for inertial navigation systems measure angular acceleration.

___ 3. Motor 2 in the simple system above must be turning if the accelerometer is sensing acceleration.

___ 4. There will be a linear distance change out of potentiometer 2 only if motor 1 is turning.

___ 5. Acceleration is integrated to obtain distance.

___ 6. An accelerometer registers velocity changes only along its sensitive axis.

___ 7. The output of the second potentiometer in the simple system above is proportional to the distance traveled.

___ 8. Accelerometers must be extremely sensitive over a narrow range of acceleration.

___ 9. Acceleration can be converted into distance by electrical or mechanical devices.

605. State how accelerometers are used by INS to determine position.

Determining Position. The system discussed above for converting acceleration into distance can tell us accurately the distance traveled in any interval of time. However, since the vehicle could have made a number of turns during the time under consideration, the system can give us no idea as to the position of the vehicle.

Suppose we mount three accelerometers on a vehicle in such a way that their sensitive axes are mutually perpendicular to one another. Then one of the accelerometers could sense acceleration along a line running east and west; a second accelerometer could sense acceleration along a line running north and south; and a third accelerometer could sense acceleration in the vertical direction. They would then be the X-, Y-, and Z-accelerometers respectively. The second integral of the X-accelerometer output gives us the distance in miles traveled in the east-west direction; the second integral of the Y-accelerometer output gives us the distance in miles traveled in the north-south direction; and the second integral of the Z-accelerometer gives us the distance, in feet or miles, traveled in the up-down direction. If, from a given point of departure, we know the distances traveled in the north-south, east-west, and up-down

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directions, we should be able at any time to pinpoint our position in space.

You may still wonder how the accelerometers know the direction in which they are sensing acceleration. The truth of the matter is that they do not know. If the accelerometers are to sense acceleration in their proper direction only, they must be mounted on a stable platform. A stable platform remains perfectly level and properly oriented with respect to true north in spite of any changes in the attitude and heading of the vehicle in its course of travel. This means that the platform on which the three accelerometers are mounted must incorporate two kinds of stabilization—azimuth and horizontal. Azimuth stabilization insures that the platform continues to point in a northerly direction in spite of any changes in the heading of the vehicle. Horizontal stabilization insures that the platform remains perfectly level with respect to the surface of the earth in spite of any pitch and roll of the vehicle.

Azimuth stabilization can be made completely automatic by making a part of a servoloop in which an inertially derived true north signal controls the azimuth of the platform. Horizontal stabilization involves cradling the platform in a system of gimbals whose position at any instant is controlled by signals originating in one or two gyroscopes. Gyroscopes, accelerometers, and stable platforms will be discussed in detail in later chapters of this volume.

Exercises (605):

1. How many accelerometers are required to pinpoint a position in space at any time?

2. What must be done with these accelerometers so that they will only sense acceleration in their proper direction?

3. What is the primary purpose of the inertially derived true-north signal in an inertial navigation system?

4. What instrument furnishes signals to the inertial stable platform for horizontal stabilization?

5. How is azimuth stabilization made automatic?

6. How is horizontal stabilization obtained?

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CHAPTER 2

Principles of Gyroscopes

IN ORDER TO CONTROL the inclination of a body or the direction of a vehicle, reference to a known orientation must be maintained. Normally, we can walk, drive an automobile, or navigate an aircraft with only a visual reference to the earth's surface. However, under severe weather conditions in which visibility is restricted and the other human senses are confused, we must establish and maintain some type of reference if we are to maneuver our aircraft along a desired course. The instrument upon which we often rely to maintain our reference is a gyroscope. Basically, a gyro is a rapidly rotating mass that is free to move about one axis perpendicular to the axis of rotation or about two axes that are perpendicular to the axis of rotation and to each other. The gyroscope has two properties that make it useful as either a stabilizing element or as a bearing indicator. These two properties are gyroscopic inertia and precession. (These terms will be explained in detail later in this chapter.)

In this course, we consider a gyro to be a rotating mass that is so mounted that intelligence may be derived from it; whereas a gyroscope is a system that contains the gyro. The information we present in this chapter is applicable to the gyroscopes that you will encounter in side-looking radar, search radar, Doppler radar, and inertial navigation systems.

2-1. Gyroscope Elements and Characteristics

Ordinary tops and small toy gyroscopes are generally driven by one pull of a string to bring their mass up to a velocity that keeps them in a stable motion for a short time. Other rather common gyroscopic examples are found in all types of spinning bodies. For instance, rifle barrels are rifled to give the bullet a spinning effect for stabilization. However, spinning objects revolving against an air cushion tend to curve rather than follow a straight line. If allowances are made for this effect, the spinning action still provides stability in a trajectory.

606. Match terms associated with the elements of a gyro with appropriate descriptions.

Elements. Note that the above examples of gyros do not have a supporting ring about their rotational axis. However, gyros used to maintain a reference must be suspended on some type of rings to permit the gyro to rotate. The gyro used in navigation systems is normally mounted in a series of interconnected rings called *gimbals*. The gimbals permit the gyro spin axis to rotate in any direction in relation to the support. The number of axes about which the gyro is free to move determines the degree of freedom. If a gyro is mounted so that its spin axis may rotate about one axis, it is a *1-degree-of-freedom* gyroscope. If it is mounted so that it may rotate about two axes, it is a *2-degree-of-freedom* gyroscope. The latter is sometimes called a *free gyroscope*, since the gyro spin axis may be placed in almost any orientation relative to the support.

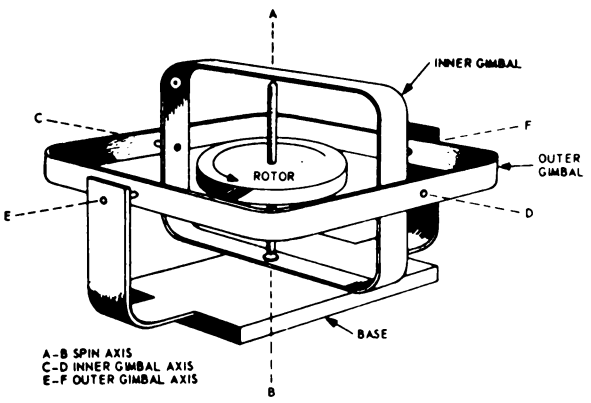

Figure 2-1. A 2-degree-of-freedom gyroscope.

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Figure 2-1 shows a 2-degree-of-freedom gyroscope. Note that the gyro is mounted in the inner gimbal which, in turn, is mounted in the outer gimbal. You can see that the gyro spin axis may be rotated about both the inner gimbal axis and the outer gimbal axis. However, if the gyro spin axis is aligned with the outer gimbal axis, or the axis of rotation of the mount, a condition known as *gimbal lock* exists. Gimbal lock causes a loss of a degree of freedom. When a 2-degree-of-freedom gyroscope is mounted in an aircraft, the orientation gimbal axes are normally fixed in respect to the pitch-and-roll axis of the vehicle. The gimbals are then referred to as *pitch-and-roll* gimbals.

Exercise (606):

1. Match each of the following statements in column A with the name of the term in column B.

Column A	*Column B*
___ 1. Allows the gyro to rotate independent of the support stand.	a. Gimbal lock.
___ 2. Gyro is aligned with one of the supporting rings.	b. Gimbals.
___ 3. Causes a loss of degree of freedom.	c. Free gyro.
___ 4. Another name for a 2-degree-of-freedom gyro.	

607. Define gyroscopic inertia and identify factors and their symbols affecting it.

Inertia. Gyroscopic inertia (rigidity) is the characteristic of a rotating mass to resist a change in the space orientation of its spin axis unless acted upon by an external force. In other words, a gyro tends to remain fixed or rigid in space.

Gyroscopic inertia is dependent upon the angular momentum of the gyro. A wheel in uniform circular motion that tends to resist any change in speed of rotation illustrates angular momentum. Angular momentum varies with the mass of the gyro, the square of the distance of the center of the mass from the spin axis, and the speed of rotation. Expressed algebraically:

$$H = MR^2 \omega$$

where

H = angular momentum

M = mass of the gyro

R = distance of center of mass from spin axis

ω = speed of rotation

High angular momentum produces great inertia. With proper gimbal mounting, this property makes a gyroscope a space reference. For instance, if a free gyro is mounted in a frictionless gimbal system and oriented with one end of the spin axis pointed toward a fixed star, the gyro will maintain this orientation. The same end of the spin axis continues to point at the fixed star regardless of earth rotation or movement of the earth in its orbit.

Exercises (607):

1. Define gyroscopic inertia.

2. What causes gyroscopic inertia?

3. List the three factors that affect gyroscopic inertia.

4. Match the following symbols to the statement defining it by placing the appropriate letter in the blank.

___ 1. M	a. Speed of rotation.
___ 2. ω	b. Distance to the center of rotation.
___ 3. R	c. Gyro mass.

608. Identify statements concerning the precession characteristic when related to the INS as true or false, and correct false statements.

Precession. Precession is the slow movement of a gyro that results from the application of any external force that tends to change the direction of its spin axis. For you to better understand how gyros are used in navigation systems, we discuss the external forces and their effects on the gyro.

Apparent precession due to earth rotation. If a free gyro is initially oriented so that its spin axis runs east and west in a horizontal plane at the Equator, its spin axis will drift in respect to the earth's surface because of the rotation of the earth. Since the gyro maintains a space

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orientation, this drift depends upon the initial orientation of the gyro and its location on the earth's surface.

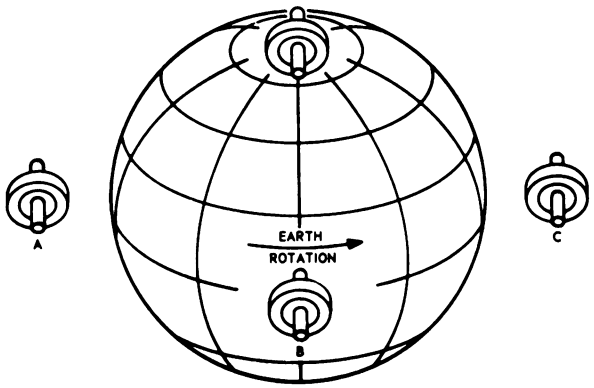

Figure 2-2. Apparent precession due to earth rotation.

Apparent precession is illustrated in figure 2-2. Point A is the initial orientation, point B is the orientation 6 hours later, and point C is the orientation 12 hours later. The earth rotates 15° per hour; therefore, a gyroscope located at the Equator and oriented as shown appears to precess 15° per hour in a vertical plane. If the gyroscope is located at the North Pole, the apparent precession is 15° per hour in a horizontal plane. On the other hand, if the gyroscope located at the Equator is oriented so that the spin axis is horizontal and runs north and south, there is no apparent precession. This is due to the fact that the gyroscope's spin axis and the earth's spin axis are aligned. Also, if a gyroscope's spin axis is oriented vertically at the North Pole, there will be no apparent precession.

Apparent precession due to vehicle movement. Apparent precession due to vehicle movement is illustrated in figure 2-3. consider a gyroscope that initially is oriented so that the spin axis runs north and south in a horizontal plane at the Equator (point A). If the vehicle is moved to the North Pole, point C, the gyroscope spin axis appears to rotate 90° in a vertical plane and is now perpendicular to a horizontal plane at the Pole. (At point B, the precession is only 45°.) Note that in each case the apparent precession is due only to the vehicle movement.

A gyroscope that is used in an aircraft for space reference is oriented with the spin axis in either a horizontal or a vertical plane. Therefore, while the aircraft is operating between the Equator and either Pole, there is a varying amount of apparent precession that depends upon the distance the aircraft has moved from the Equator. Consequently, to

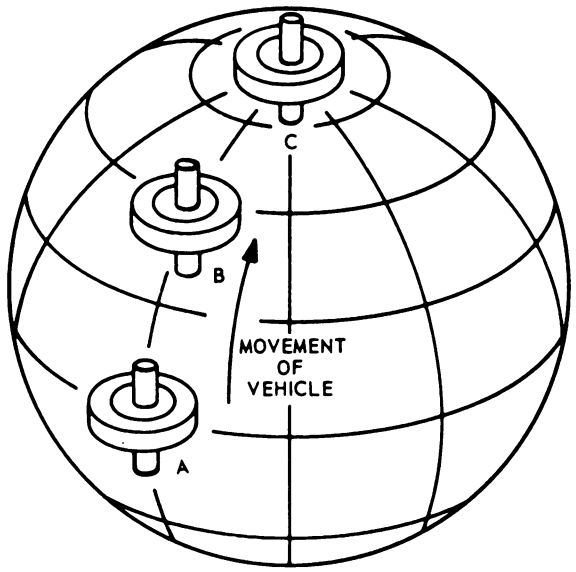

Figure 2-3. Apparent precession due to vehicle movement.

maintain a reference at some specific point on the earth, the gyroscope must be torqued (moved, or displaced) an amount that is opposite and equal to the apparent precession. That is, forces must be applied to the gyro in such a manner that the gyro maintains the desired earth orientation.

Precession due to torque. Gyroscopic precession is that characteristic that causes the gyroscope to rotate in a place perpendicular to the direction of the applied force. When a force is applied to disturb the axis of rotation, the gyro spin axis moves about an axis at right angles to the disturbing force. The direction in which it moves depends upon the direction of the disturbing force and the direction of the spin of the gyro.

For a simple illustration of precession, consider the action of a spinning top. When the top begins to spin, it is moving rapidly and is in an approximately vertical position. As the top begins to slow down, it leans from the vertical position and its head moves in almost a perfect circle while maintaining an angle of tilt from the vertical position. If a line is extended upward from the center of the top, it inscribes an inverted cone in space, with the point of the top being the apex. This line is the spin axis of the top, and its motion in azimuth is precession. Thus, a rapidly spinning top

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illustrates the action of a gyro with no force applied, and simulates rigidity. As the top slows down, it illustrates the action of a gyro with an external force applied and, therefore, simulated precession. When the force applied is not through the center of gravity of the gyro, the direction of precession is always in the direction of the spin. If a free gyro is acted on by a torque in a plane through the gyro axis, the axis precesses in a plane perpendicular both to the plane of the spin and to the plane of the torque.

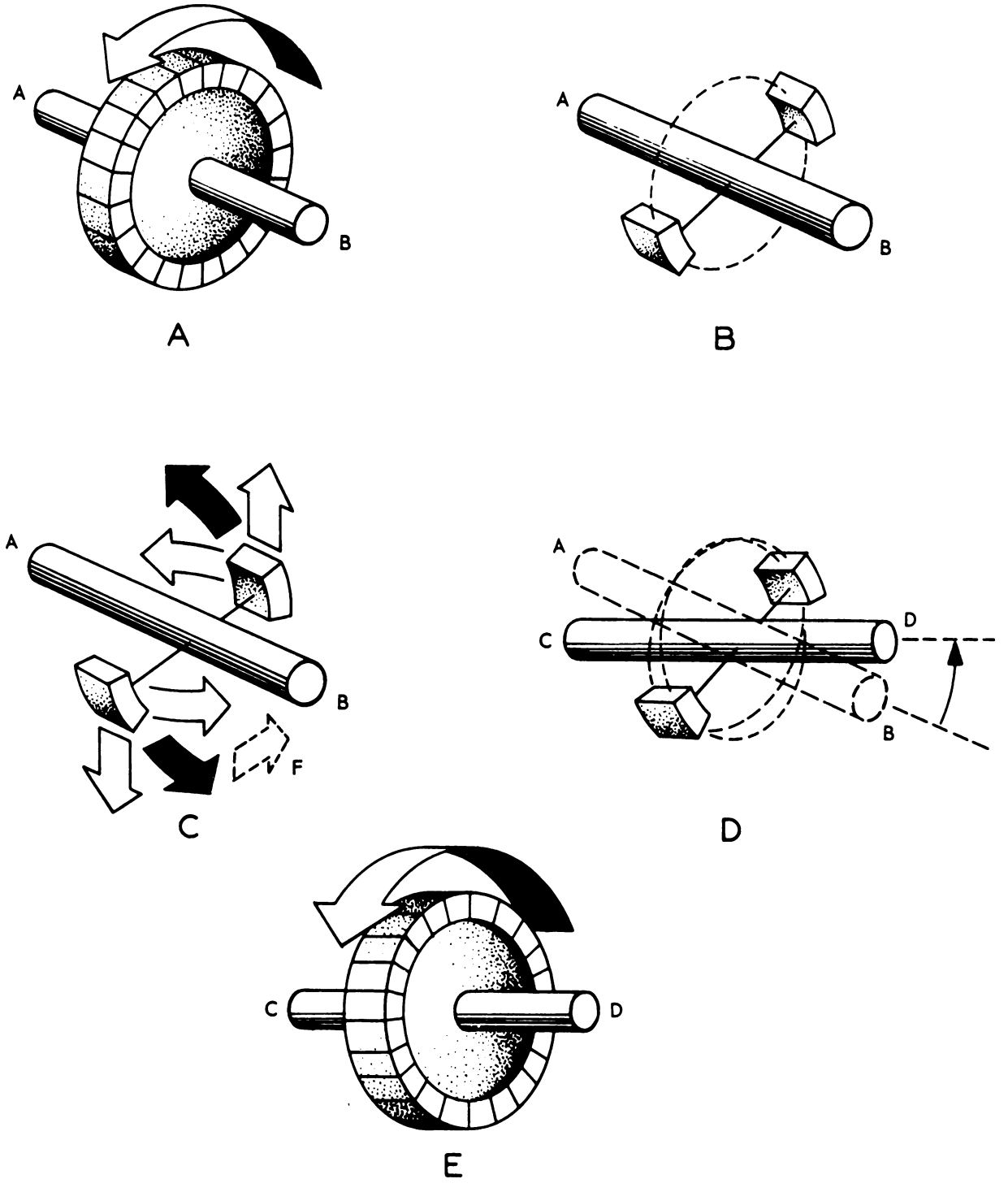

Figure 2-4. Gyro precession due to torque.

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For a better understanding of the preceding statement, refer to the illustrations in figure 2-4. Figure 2-4,A, shows the rotor rotating rapidly about axis A-B, in the direction of the arrow. For simplicity, consider the rotor as being made up of a series of segments. We will use only two segments, rigidly connected to axle A-B and exactly opposite to each other (fig. 2-4,B). As axle A-B turns, one segment moves up while the other moves down. A horizontal force (F) applied to axle A-B turns, one segment moves up while the other moves down. A horizontal force (F) applied to axle A-B (fig. 2-4,C, dotted arrow) has a tendency to move the segments, one to the right and one to the left. The segments now have horizontal and vertical motion, as illustrated. Note that the segments actually move diagonally because of the horizontal and vertical motion. The resultant movement is illustrated by the dark arrows. As the segments move diagonally, they are forced to rotate about axis C-D (fig. 2-4,D), which lies in a plane perpendicular to the force applied. All other segments being rigidly connected to the axle must tilt the same way, causing the axle to align itself with axis C-D, thus making the gyro tilt. Figure 2-4,E, shows the final result of the horizontal force applied to axle A-B.

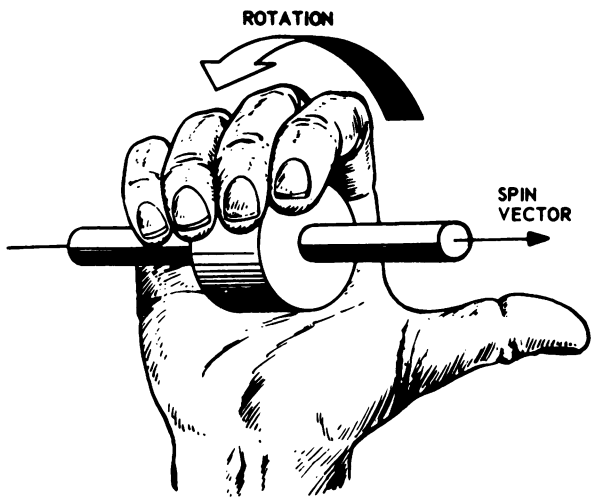

Figure 2-5. Right-hand rule.

Illustrating precession with vectors. Gyroscopic precession may also be explained by the use of vectors. This method of representation is very useful because the direction of the precession can be predicted. A vector is a representation of a force, velocity, acceleration, or other physical quantity. Any of these physical quantities have magnitude and direction. The magnitude is represented by the length of the vector, and the direction is represented by the relative position of the arrowhead.

Since a rotating mass has magnitude and direction, the rotation may be represented by a vector. The length of the vector is scaled to represent the magnitude of the rotation in terms of degrees per second, revolutions per minute, or other appropriate terms. The direction of the vector is determined by the right-hand screw rule; that is, the vector arrow points in the direction that a screw will advance, if turned in a clockwise direction, when viewed from the head of the screw. The right-hand screw rule is illustrated in figure 2-5. With the fingers pointed in the direction of rotation, the thumb points in the direction of the spin vector arrow.

Figure 2-6 illustrates the three vectors we must consider in explaining gyroscopic precession. The first of these vectors, the spin vector, simply represents the gyro rotation. The second is the torque vector, which represents the force applied to one of the gimbals. The third is the precession vector, which represents the rotation of the gyro spin axis due to the applied torque. By applying the right-hand

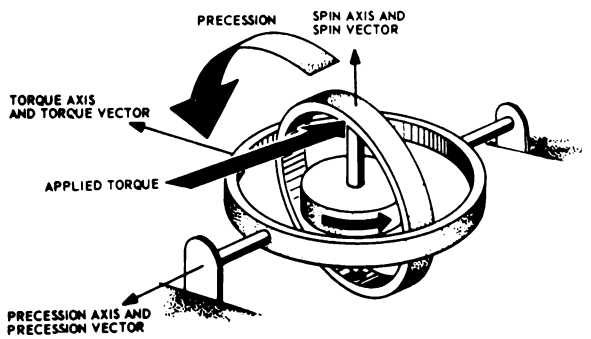

Figure 2-6. Gyroscope vectors.

screw rule, we can determine the spin vector and the direction of rotation of the gyro. Your right hand can also be helpful in determining the relationship of the spin, torque, and precession vectors. Arrange your thumb, index, and middle fingers into three quadrature axes, as illustrated in figure 2-7. Assume that your thumb is pointing in the direction of the spin vector and that your index finger is pointing in the direction of the torque vector. Keep your fingers rigidly in this configuration. When you try to rotate your thumb (spin vector) into your index finger (torque vector), your hand

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(the gyro) moves around your middle finger (precession axis)—just as the gyro moves as it precesses. In addition, the middle finger points in the direction of the precession vector.

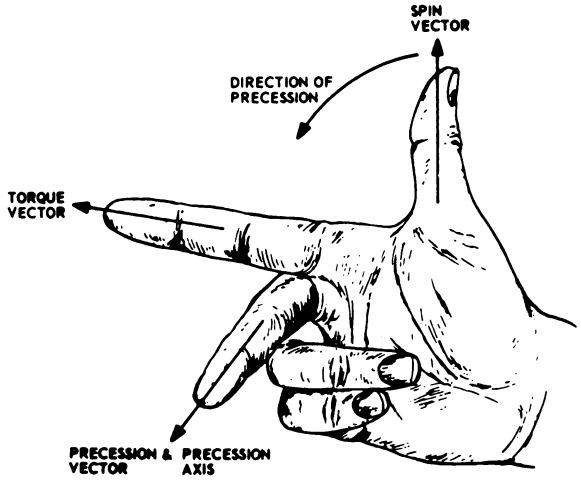

Figure 2-7. Gyroscope right-hand rule.

Note that the gyroscope is sensitive to torque or motion about the axes perpendicular to the spin axis. In other words, the gyroscope is not sensitive to torque or motion about the spin axis. Therefore, when the spin vector becomes aligned with the torque vector, there is no further precession.

Exercises (608):

Identify each statement as true or false; if a statement is false, correct it.

___ 1. Precession results from a force applied parallel to the spin axis.

___ 2. Precession caused by torque is real precession.

___ 3. Vehicle movement causes apparent precession.

___ 4. Earth rotation causes real precession.

___ 5. The maximum precession due to earth rotation is 15° every 6 hours.

___ 6. Apparent precession due to earths rotation is 15° per hour in the vertical plane at the equator, assuming that the gyro is east-west oriented.

___ 7. Apparent precession can occur due to the earths movement or vehicle movement.

___ 8. The rotation and precession of a gyro may be shown by vector diagrams where the quantities are related in accordance with the right-hand screw rule.

___ 9. A gyro is sensitive to torque about the spin axis.

___ 10. When the spin vector and the torque vector representing gyro force are in alignment the precession rate is maximum.

609. Complete statements that explain how a gyro can be used as a compass.

Gyrocompass Effect. A gyroscope, rigidly mounted on the earth's surface, will seek true north. This is illustrated in figure 2-8. Note that the rotor has only 1-degree-of-freedom, since it has only one gimbal ring. The spin axis is allowed to rotate only in a horizontal plane. Since any gyroscope maintains its position with reference to a point in free space, the gyro tries to remain as drawn. The earth's rotation (note arrow) forces the top of the gyro away from its space reference. The gyro rotor attempts to maintain this reference by tilting the rotor axis to points C-D. Because of the mounting arrangement, the rotor cannot tilt and, therefore, exerts a twisting pressure on the gimbal ring at points A-B. A force equal to that of the rotor is exerted by the ring as it maintains the rotor in the horizontal plane.

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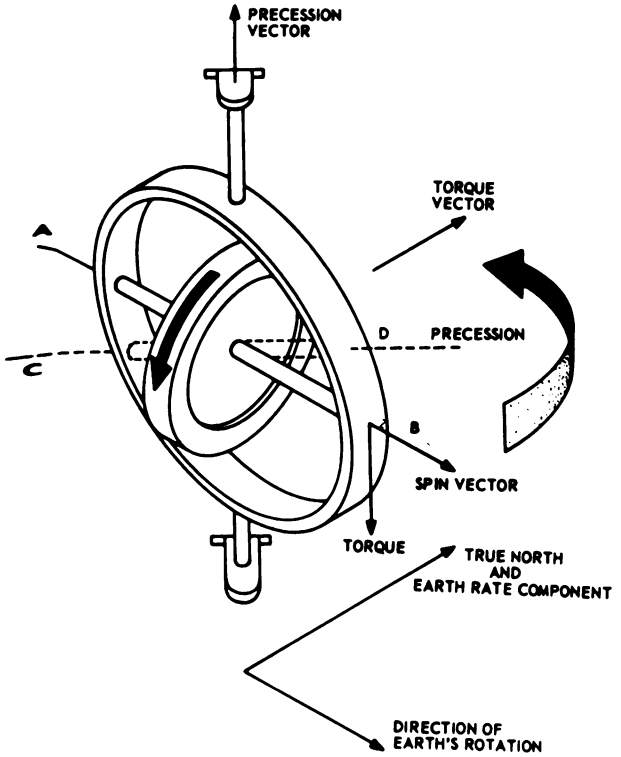

Figure 2-8. Gyrocompass.

This force is effective at point B and is in the direction of the arrow marked "torque."

We know from our study of gyros that when an applied force disturbs the axis of rotation of the gyro, the gyro moves about an axis that is at right angles to the disturbing force. This action causes our gyro rotor in figure 2-8 to swing counterclockwise as long as this force is present. When the rotor axis has turned so that it points true north/south, the pressure is no longer felt. The rotor rotation is then the direction of the earth's rotation and there is no longer a twisting force applied to the rotor axis.

Exercises (609):

1. A gyro utilized as a compass has_____ gimbal(s).
2. A gyro utilized as a compass will seek____ _____.
3. A gyro utilized as a compass has its spin axis orientated in a_____plane.

2-2. Operation of a Typical Gyroscope

Gyroscopes vary in size, shape, and complexity, but their manner of operation is similar. Gyroscopic rigidity is attained from a gyro rotor having a high velocity of rotation. A gyro rotor may be made to spin by an air jet, a clock spring, an explosive cartridge, or an induction motor. The latter is the one most commonly used.

610. State operational principles and describe functions of typical gyro components.

Components. When an induction motor is used to spin the gyro, the motor itself is the major part of the gyro. The rotor of the induction motor is on the outside and the stator is on the inside, unlike most motors. Figure 2-9 illustrates this construction. The stator is the central part of the gyromotor, and the rotor with its mass rotates around it. Three-phase (400-Hz) power is supplied by three wires that run through the hollow stator shaft to the stator. Note the mass, which is added on the rotor, effectively gives a greater radius, and hence, greater angular momentum. To maintain the angular velocity, and therefore, the angular momentum exact and constant, precise voltage with precision frequency is used to spin the gyromotor. This is necessary in order to reduce drift of the gyro and to maintain constant torquing signals. This will be explained shortly. The gyromotor is encased as illustrated in figure 2-10. The motor and its housing are then referred to as a *float assembly.* The float assembly is pivoted inside another case, using a gimbal ring (fig. 2-11,A). The case that houses the float assembly is the gyro case. The pivot between the float and the gyro case provides 2-degrees-of-freedom, as illustrated (vertical and horizontal). We now have a complete assembly.

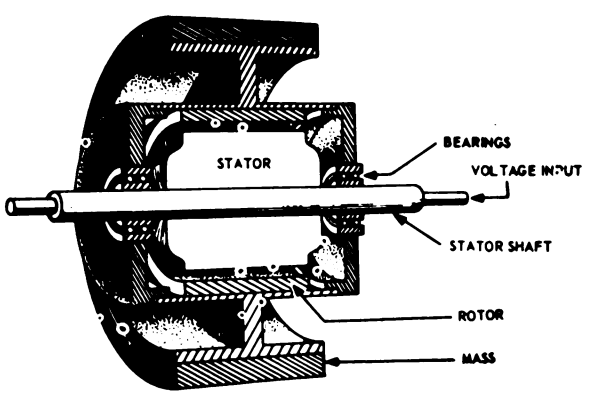

Figure 2-9. Gyromotor

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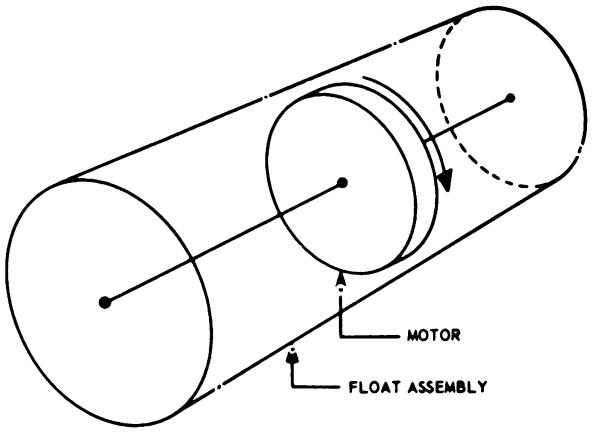

Figure 2-10. Float Assembly.

Gyroscope Stabilization. Once the gyromotor attains the desired speed, it maintains its spin axis relative to a point in free space. Since the motor is an integral part of the float assembly, the entire float assembly will remain oriented to this point. Moving the end of the gyro case up or down varies the relative position of the float assembly within the case. Although this movement is small, it can be detected by mounting pickoff coils on the float assembly as illustrated in figure 2-11,A. These pickoff coils obtain an AC voltage, through transformer action, from excitation coils mounted on the gyro case. As the relative position of the float and case is varied, so is the relationship of the pickoff and excitation coils. Movement of the case around the float assembly causes the pickoff coils to be closer or farther from their excitation coils. Consequently, one pickoff coil senses an increasing voltage while the other senses a decreasing voltage. The direction of the change depends upon the direction of the movement.

By winding either the excitation coils or pickoff coils 180° out of phase, we have a means of detecting the direction of case movement. The amplitude of the detected voltage is analogous to the amount of movement. The voltage sensed by the pickoff coils is called an *error voltage*, since it represents the displacement error between the float assembly and the gyro case. In a working model, this error voltage is amplified and used to drive a

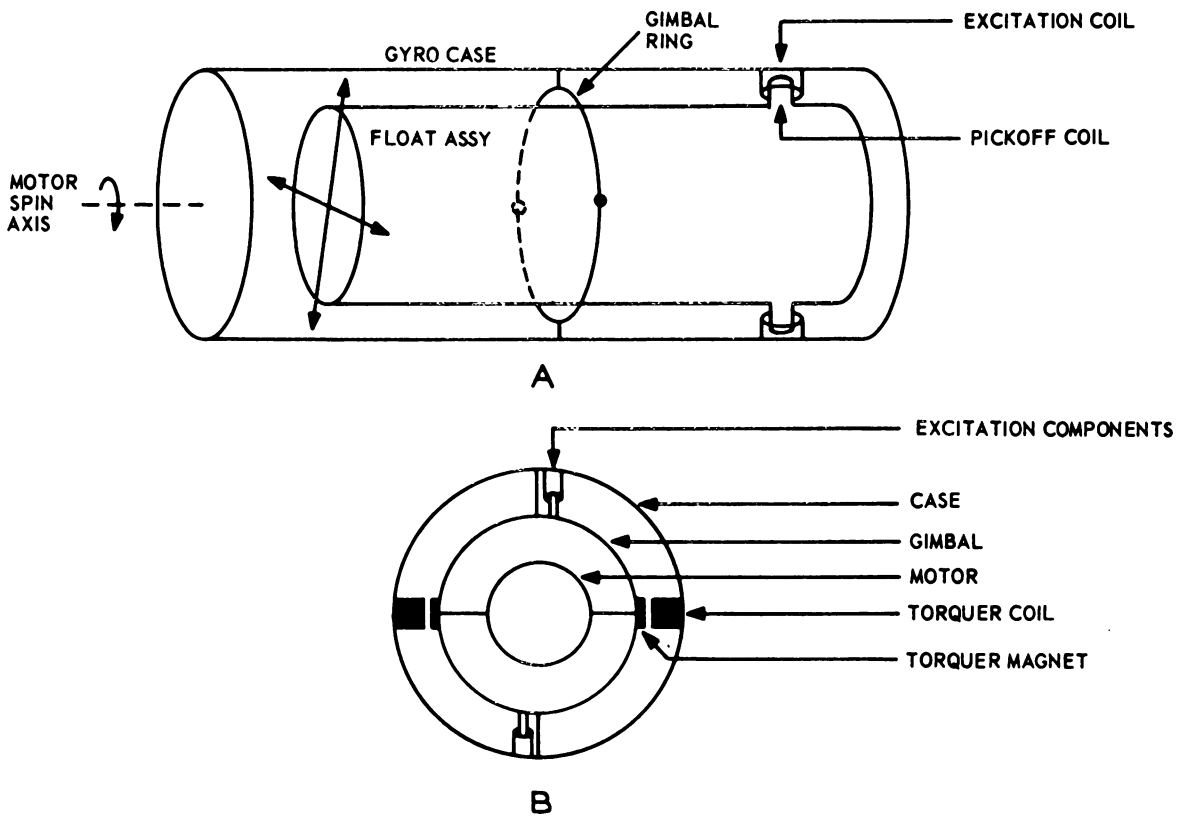

Figure 2-11. Gyro.

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motor that repositions the case (through its gimbals) until it is realigned to the gyro spin axis. This system illustrates only 1° of stabilization.

Why not use two gyros perpendicular to each other and let their error signals stabilize a common element, such as a platform or an antenna? By using the two gyros, our common element will have 3° of stabilization (i.e., pitch, roll, and azimuth). This is precisely what is done in the inertial navigation system. By mounting accelerometers on this stabilized platform, we insure that they sense accelerations only along their sensitive axis.

Gyroscope Torquing. In our discussion of gyroscopes, we have assumed that a gyro functions perfectly and that the gyro spin axis does indeed stay fixed in space. Unfortunately, this is not quite true in reality. Any friction of pickoff coils or gimbal bearings, and any imperfection of the gyro rotor-stator exerts undesirable torque. The complex mechanical structures associated with gyroscopes give rise to many such torques. Any displacement of the rotor as a result of unwanted torque is referred to as *random drift.*

It seems as if we have a problem on our hands. We want to make use of the space stable properties of the gyro, but the stable reference line, to be useful, must be lined up with the local vertical. Because of random drift due to unknown torques, the space stable line appears to drift with respect to the earth's vertical. It is evident that some corrective measures must be taken to keep the gyro spin axis lined up with the local vertical.

To use the gyroscope in navigation equipment, we must correct for random drift and apparent precession that are due to earth and craft rate. To counteract these unwanted torques, the gyro must be torqued (moved or displaced) an amount opposite and equal to the unwanted torques. That is, the orientation of the float in respect to a reference is maintained by means of computed torquing signals. Note in figure 2-11,B, the placement of components necessary for proper operation. Note that the torquing coils and magnets are displaced 90° around the case from the pickoff components. This placement is necessary because a gyro precesses about an axis that is 90° away from the applied force.

The computed direct-current torquing signals are applied to torquing coils mounted on the float assembly. The magnetic field caused by the direct current applied to the torquing coils works against the magnetic fields of the permanent magnet mounted on the gyro case. The interaction of the two magnetic fields causes a torque on the float and precesses the gyro at the proper rate in a direction to maintain the desired orientation.

Exercises (610):

1. What is the purpose of the added mass on the rotor of a gyro?
2. What is the major part of a gyro?
3. Why is it important that a precision frequency and voltage be used to spin the gyromotor?
4. Where do the gyro pickoff coils obtain an AC voltage proportional to the movement of the gyro case?
5. What means do we use to detect the direction of case movement?
6. Why is it necessary that the torquing components be displayed 90° around the gyro case from the pickoff components?
7. What is contained in the gyro float assembly?
8. What causes random drift?
9. What type of voltage is used in the pickoff coils?
10. How many gyros are necessary for full 3° of platform stabilization?

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Principles of Accelerometers

AN ACCELEROMETER, as its name implies, is a mechanism that senses acceleration. The importance of this sensing capability lies in its measuring distance and direction traveled without reference to any other navigation aid—seen or unseen.

In your work as a specialist and later as a technician, you will be responsible for the maintenance of equipment, which includes accelerometers. If you are to be successful in your job, it is important that you thoroughly understand accelerometers and the operation of circuits associated with them. In this chapter, we discuss acceleromoters and the signals necessary to insure their proper operation. However, before we explain the principle of operation of an accelerometer, it is necessary for you to understand the laws of motion upon which the principle is based.

3-1. Laws of Motion

By the time a person has graduated from high school, he or she has been well indoctrinated with the tale (or fable) about Newton—who had little else to do but sit under trees watching apples fall. His laws of motion have become universally known and applied. More appropriately, they govern the action and reaction of accelerometers. We mentioned these laws briefly in objective 603. In this section, we will study them more thoroughly and see how they are applicable.

611. State Newton's laws of motion and given a situation, specify which law is applicable.

Newton's Laws. Sir Isaac Newton developed three laws of motion that form the basis for practically all of the theories of mechanics. These are the:

- Law of inertia.
- Law of momentum.
- Law of reaction.

The law of inertia states that "a body at rest tends to remain at rest, whereas a body in linear uniform motion tends to remain in the same uniform motion; unless it is acted on by an outside force." (On or near the surface of the earth, gravity must be contended with as an outside force.)

The law of momentum states that "when a force acts upon a body, it changes the momentum of that body. The change in momentum is proportional to the applied force and to the time that this force acts upon the body." According to Newton,

$$M = mV,$$

where M = momentum
m = mass
V = velocity

Since mass does not change, only velocity can affect the momentum of a body by an applied force accelerating it. (Deceleration is negative acceleration.) In the next objective, we show how acceleration changes velocity.

The law of reaction states that "every action (force) is resisted by an equal and opposite reaction (force)." For example, if a 10-pound weight is placed on a table, the table must exert an upward force of 10 pounds in order to support it.

Exercises (611):

1. State Newton's three laws of motion.

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2. Which of Newton's laws is applicable to a 150-pound person sitting in a chair?

612. Using the formulas for the relationships of acceleration, time, and distance and/or velocity, solve for the unknown quantity when related values are known.

Distance. Before we apply Newton's laws, we need to define some basic terms that are commonly used. The first considered here is time. Everything we do involves time, but exactly what is it? Can it be defined? Time, a fundamental quantity, is simply the measurement of some recurring event. The most common reference is the rotation of the earth, which is divided into 24 hours; each hour is divided into 60 minutes, and each minute into 60 seconds. Other recurring events such as the stars are sometimes used depending upon the application.

Distance is a term that also needs to be defined. Distance, another fundamental quantity, is the measurement between two points by a standard of length. Depending upon what two points we select, here is a variety of measurements available to use. For long measurements, say, between two cities, miles or kilometers are commonly used. For short measurements, feet or meters are more practical.

Velocity. Velocity is the rate at which an object changes its position with respect to time. It is expressed in terms of distance traveled in a unit of time in a known direction. Notice that velocity is expressed by the two fundamental terms just defined above, time and distance. For instance, if we say the wind velocity is 20 miles per hour to the west, we have defined velocity in terms of distance and velocity.

Another term often confused with velocity is speed. Speed and velocity are not the same.

If we say the wind is 20 miles per hour, we are giving its speed and not its velocity. Speed is the rate at which an object is moving without regard to direction. Speed is expressed in terms of distance in a unit of time (the same as velocity) but direction is not specified. Velocity is a vector quantity and speed is a scalar quantity.

In the real world, as vehicles travel any appreciable distance, velocity is subject to many changes and variations. However, there is a need for a specific velocity useful in basic computations of distance, time, and velocity. Thus, it is convenient, and sufficiently accurate, to use the *average velocity*.

Average velocity is:

$$\overline{V} = \frac{d}{t} \qquad (1)$$

where V = average velocity

d = distance

t = time

For example, if it takes 2 hours to go 20 miles due east, the average velocity for the trip is 10 miles per hour to the east. It is called an average velocity because we do not know anything about what happened to the velocity between points A and B. We could have varied our velocity throughout the trip or maintained it constant and the average could be the same.

Acceleration. To find out what happened between points A and B, we need to know about the acceleration of the object.

Acceleration of an object is the rate of change of its velocity with respect to time. Acceleration can be felt when you step down on the accelerator pedal of your automobile and the force pushes you back into the seat. Assuming an object initially at rest is accelerated at a constant rate, the velocity it attains at the end of time (t) is:

$$\text{velocity} = \text{acceleration} \times \text{time}$$

$$V = at$$

When the velocity changes uniformly with time, the average velocity in any time interval equals one-half the sum of the speeds at the beginning and at the end of the interval. We know from the above that for a body initially at rest, the final velocity is $V = at$. We may express average velocity as:

$$V = \frac{at}{2} \qquad (2)$$

Example: If an automobile is linearly accelerated from a dead stop at 20 miles (hour)2, what is the average speed after 1 hour? (Remember, speed is velocity without direction.)

$$V = \frac{20 \frac{\text{miles}}{2} \times 1 \text{ hour}}{(\text{hour})^2} = 10 \frac{\text{miles}}{\text{hour}}$$

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If we solve formula (1) for distance

$$d = Vt$$

and substitute formula (2) for $\overline{V}$

$$d = \frac{at \times t}{2} = \frac{1}{2} at^2$$

now let us solve the example for distance:

$$d = \frac{1}{2} \times 20 \frac{\text{miles}}{(\text{hour})^2} \times (1 \text{ hour})^2$$

$$d = 10 \text{ miles}$$

Let us now suppose that the body was initially in motion with a given velocity. In this case, the average velocity of the body becomes

$$\overline{V} = Vo = \frac{Vf - Vo}{2}$$

where Vf = the final velocity at the end of some time period t, assuming uniform acceleration

Vo = the initial velocity at the beginning of time t

Thus, the expression for distance becomes

$$d = \overline{V}t$$

$$= (Vo + \frac{Vf - Vo}{2})t$$

Having shown the mathematical relation between acceleration, velocity, and distance, we have established the basis for taking accelerometer readings and converting them into velocities or distances.

Exercises (612):

1. If a person ran 300 meters in 15 minutes, what was the average speed? What is the difference between speed and velocity?

2. a. An automobile linearly accelerates at 48 kilometers per (hour)2 for 5 minutes from the starting line, what is the average speed?

   b. What is the distance traveled at the end of 15 minutes?

3-2. Accelerometer Requirements

When an object is designed for a particular use, certain specifications must be met and limitations or design problems overcome. Designing the ideal accelerometer is no exception. In this section, some of these problems will be discussed.

613. State and explain the characteristics of an accelerometer.

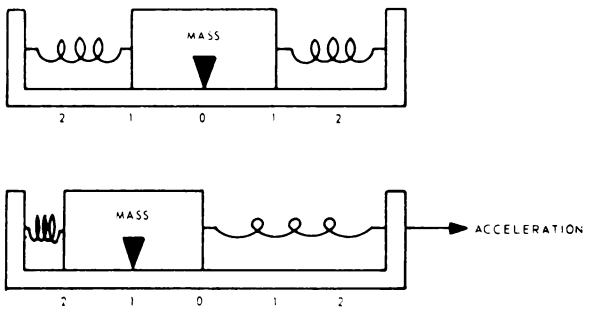

Figure 3-1. Sensing acceleration with block and slide.

There are a number of ways of sensing acceleration. One way is illustrated in figure 3-1. Here, we have a block resting on a frictionless slide and tied to the ends of the slide by means of springs. If the slide is accelerated in the direction indicated, the block experiences a force that causes it to move in the opposite direction. The direction the block moves against the restraining force of the springs varies directly with the acceleration imparted to the block. Hence, by mounting a pickoff between the block and the slide, a measure of the acceleration experienced by the block can be easily obtained.

A second method of sensing acceleration is illustrated in figure 3-2. Here, we have a mass suspended on a pivot and restrained by two springs. Accelerating the device in the direction indicated causes the mass to deflect. The amount of deflection may be taken as a measure of acceleration.

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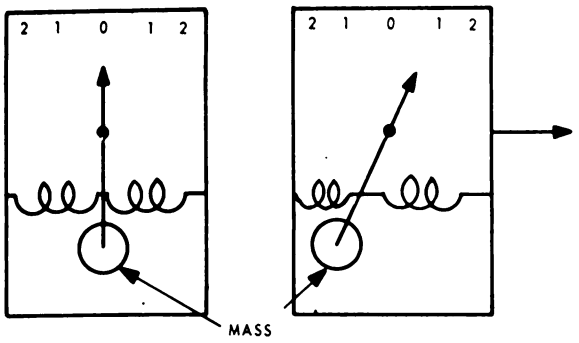

Figure 3-2. Sensing acceleration with a pendulum.

The desired characteristics of an accelerometer are:

- Low threshold of sensitivity.
- Wide range of sensitivity.
- Linearity.
- High resolving power.

The threshold of sensitivity is the smallest acceleration that the accelerometer can sense. Range of sensitivity refers to the extent from the least to the maximum acceleration that the accelerometer can sense. Linearity is the capability of the accelerometer to produce an output that is directly proportional to acceleration. High resolving power is the ability to discern small increments of change.

The two types of accelerometers illustrated can be considered linear only near their null or neutral position. Any displacement from the neutral point changes the constants involved. For example, the spring constants tend to be different for different amounts of acceleration. Also, when the pendulum is displaced from the center of the arc, an undesired component of gravity acts upon it. These problems make it difficult to mechanize accelerometers so that they provide linearily over a wide range of sensitivity.

Exercises (613):

1. What do we call the smallest acceleration that the accelerometer can sense?

2. What term describes an accelerometer characteristic that is based on an output that is directly proportional to acceleration?

3. At what point can the accelerometers described in figures 3-1 and 3-2 be considered linear?

4. What does the term "high resolving power" refer to in an accelerometer?

5. Why are accelerometers not proportional to acceleration in all regions of their operational range.

6. What is meant by the range of sensitivity?

3-3. A High-Precision Accelerometer

In the preceding section, we presented the principle of operation of accelerometers in general. We are now ready to study an actual working accelerometer. We have selected for consideration one of the accelerometers used in stabilizing the platform of an inertial navigation system. The major subassemblies of this accelerometer are shown in figure 3-3 and include the sensitivity element (pendulum), the case assembly, and the cover. We describe these items and then tell you something about the theory of operation and the precision resistors.

614. State the purpose of components and describe operational principles of a high-precision accelerometer.

The Sensitive Element. The sensitive element is a rectangular structure having a pivot on each side and a ringlike torquer coil at each end. Suspended below each torquer coil is a pickoff coil. An adjustable weight is threaded into one end of the pendulum. This weight permits precise balancing adjustments of the pendulum.

The Case Assembly. The case assembly is a rectangular box that contains two sets of exciter coils at each end, a jewel bearing on each side, an expansion bellows on its base, and five electrical terminals on one side. When the pendulum is in place, each pivot fits in a jewel on each side of the case, and each pickoff coil

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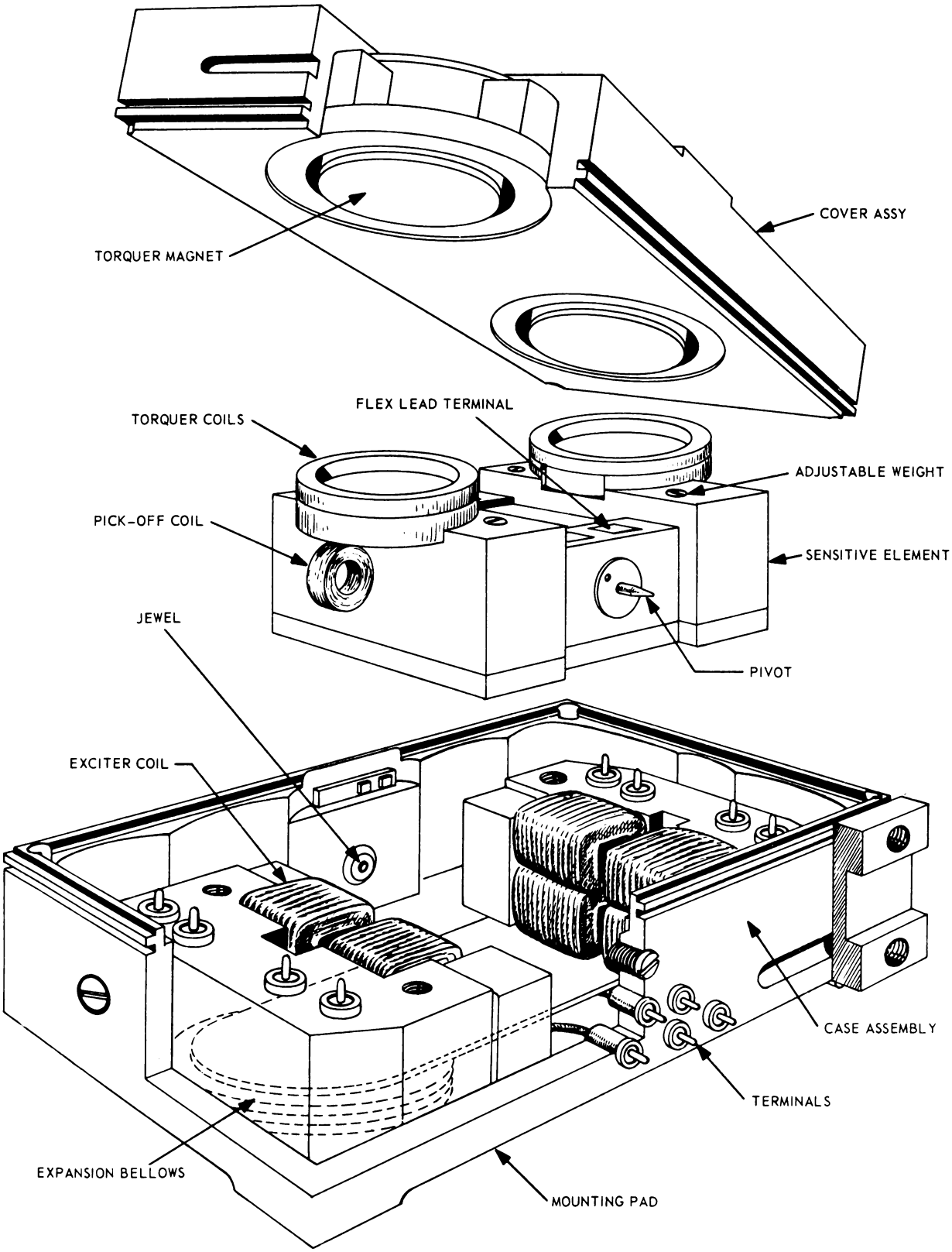

Figure 3-3. Major accelerometer subassemblies.

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fills the void between the exciter coils at each end of the case. The ends of the torquer coil are brought to two terminals on the pendulum. These two terminals are, in turn, connected by means of two very fine flexible leads to two of the terminals on the side of the case assembly.

The case assembly is filled with a high-density, low-viscosity fluid known as *fluorolube*. The fluorolube serves one main purpose—it floats the pendulum, thereby removing all weight from the jewel bearings. Thus, bearing friction is reduced to a minimum. A secondary function of the fluorolube is to serve as a damping agent for the pendulum. The expansion bellows at the base of the case compensates for thermal expansion of the fluid.

The Cover Assembly. The cover assembly is a rectangular structure that houses two cylindrical permanent magnets. When the cover is lowered over the case assembly, each magnet fills the void within the torquer coil.

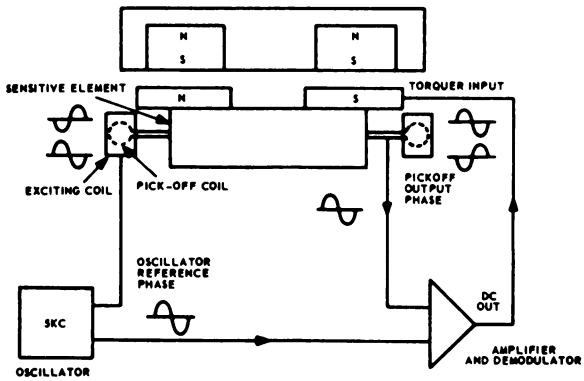

Figure 3-4. Accelerometer operation.

Theory of Operation. The theory of operation for this accelerometer may be explained with the aid of figure 3-4. Reference to this figure will show two items not previously mentioned—the 5-kHZ oscillator and the restoring amplifier and demodulator. The 5-kHZ oscillator feeds a 5-kHZ reference signal to both sets of excitation coils in the case assembly and to the input of the restoring amplifier and demodulator.

When the accelerometer is subjected to an acceleration along its sensitive axis, the pendulum tends to be displaced from its null position. The resultant displacement of the pickoff coils with respect to the excitation coils results in a signal being generated. This signal is transmitted to the restoring amplifier and demodulator where an output is developed for the torquer coils on the sensitive element. The current made to flow through the torquer coils is in a direction to oppose the acceleration and to return the pendulum to its null position. The torquer current is directly proportional to the applied acceleration and becomes the acceleration output signal. The pickoff signals are developed and the torquer currents are applied in the same manner as those on the gyroscope that we discussed in the preceding chapter.

We can see that it is possible to counter the acceleration-produced torque on the float by introducing into the torquer coils a torquing current. The polarity of this current influences the direction of the torque. It is the function of the pickoff signal to dictate to the torquer coil (through the demodulator and restoring amplifier) the direction of the current flow. If the pickoff signal is in phase with the excitation reference signal, then the torquer current is in one direction. If the pickoff signal is out of phase with the excitation signal, then the direction of the current is reversed.

If the left side of the sensitive element in figure 3-4 is displaced downward, then the output signal from the pickoff coils will be in phase with the excitation reference phase. These two inputs to the restoring amplifier cause it to feed out a positive direct current. This positive current causes a torque about the pivot to restore the sensitive element. As long as there is *some* pickoff signal, the current remains to hold the float in the null position. The acceleration signal is the voltage developed when the torquer current flows through a precision resistor.

Precision Resistors Used in Accelerometers. There are several precision resistors used in accelerometers. They are used for scale factoring, biasing, temperature compensation, and for correction of quadrature. We discuss each resistor separately in the following paragraphs.

Scale factor resistor. We mentioned above that the accelerometer signal is the voltage produced across a precision resistor by the torque current that is made to flow through the resistor. By properly selecting the value of this resistor, we can make it serve as a scale factor. We mean by this that its value can be selected so that the voltage across it will be 1 volt/g, 2 volts/g, or any desired scale. The most common scale factor used is 2 volts per g of acceleration.

The average current required to null an accelerometer at 1 g of acceleration is about 2.5 milliamperes; however, this current varies with each individual instrument. For this reason, the scale factor resistors must be calculated according to the scale factor current of each

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individual accelerometer. The calculation is a simple one. Knowing the voltage we desire at the top of the resistor and the current going through it, we can simply state that the resistance is equal to the voltage divided by the current.

Bias resistor. The next resistor to be considered is the bias resistor. If we subject an accelerometer to 1 g of acceleration along its sensitive axis and measure the current required to hold it in the null position, then invert the accelerometer 180° and measure the current required to again null it, the two currents should be equal but of opposite polarity. If they are not equal, by taking the difference between the two currents and dividing by 2, we can find the bias of the instrument. The difference in currents could be caused by inconsistency in the mass, an eccentric pivot, or unbalanced spring rate of the instrument. The bias usually is in the area of 1 microamp of current.

Temperature compensating resistor. This resistor assures a constant scale factor regardless of changes in temperature.

Quadrature resistor. Approximately 1 of every 15 accelerometers requires the fourth resistor—that is, a quadrature resistor. The quadrature resistor is one that compensates for a 90° phase shift between the excitation coil and the pickoff coil. The phase shift is due to the capacitance between the two coils. Since no two accelerometers can ever be made exactly alike, the distance or capacitance between the excitation and pickoff coils will be different with different accelerometers. The phase shift cannot be corrected for in the amplifier; therefore, it remains inherent in the pickoff output. In order to correct for the phase shift, a resistor is placed across a center tap of the excitation coils. This resistor shifts the phase back 90° compensating for the original lead of 90° introduced by the capacitance.

The precision resistors described above are mounted on a small module on the accelerometer. These resistors are an integral part of the accelerometer and serve to make the accelerometer interchangeable with other accelerometers from the same manufacturer.

Exercises (614):

1. What is the purpose of the adjustable weight that is screwed into one end of the pendulum?
2. Why is the case assembly filled with fluorolube?
3. What is the function of the 5-kHz oscillator?
4. What is the relationship between the torquer current required to null an accelerometer and the applied acceleration?
5. What determines the direction of the current flow necessary to null an accelerometer?
6. What does the voltage across the scale factor resistors represent?
7. Why is it necessary to calculate the value of the scale factor resistors for each accelerometer?
8. Why does the amount of bias current necessary to null an accelerometer vary with each instrument?
9. What is the purpose of the quadrature resistor?
10. Which accelerometer subassembly houses the permanent magnets?
11. What is the purpose of the expansion bellows?
12. What component prevents the scale factor from varying with changes in temperature?
13. What is the most common scale factor developed across the scale factor resistor?

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CHAPTER 4

Principles of Stable Platforms

IN OUR INTRODUCTION to the principles of inertial navigation, we learned that this method of navigation involves knowing the latitude and longitude of the point of departure of our vehicle, and adding to the initial latitude and longitude, all increments of change that the vehicle experiences from the moment of departure.

At this point, you wonder what is new about this. This is nothing other than the principle of dead-reckoning navigation. The thing that is new about inertial navigation is that the increments of change in latitude and longitude are derived from two accelerometers. One accelerometer must be oriented on the vehicle in such a way that it senses only components of vehicle acceleration in the north-south direction, and the other accelerometer must be oriented so that it senses only components of vehicle acceleration in the east-west direction.

At this time, you may also wonder how accelerometers can be mounted in an aircraft so as to retain their desired orientation in spite of all aircraft maneuvers. In answer, they must be mounted on a stable platform—which brings us to the subject of this chapter.

4-1. Platform Principles

Before discussing inertial platform principles or any of its component parts, we must review some of the terms we will be using.

615. Specify the axes and angles associated with aircraft attitude.

Definition of Terms. The aircraft moves about three orthogonal axes—that is, the longitudinal, lateral, and yaw, or vertical axes (illustrated in fig. 4-1). The longitudinal axis runs fore and aft in the plane of symmetry and is the axis about which the aircraft rolls. The lateral axis runs from side to side and is perpendicular to the plane of symmetry and to the longitudinal axis. The aircraft pitches about the lateral axis. The yaw axis lies in the plane of symmetry perpendicular to the longitudinal axis and is the axis about which the aircraft yaws or turns.

Roll angle. The roll angle is the angle between the aircraft lateral axis and a horizontal plane. This angle is measured in a vertical plane and has a maximum value of ±180°, at which time the aircraft is inverted. A *positive roll* angle is clockwise or right wing down, and a *negative roll* angle is counterclockwise or left wing down.

Pitch angle. The pitch, or elevation, angle is the angle between the aircraft longitudinal axis and a horizontal plane. This angle is measured in a vertical plane and has a maximum value of ±90°, at which time the aircraft is going straight up or straight down. A *positive pitch* angle is nose up (climb), and a *negative pitch* angle is nose down (dive).

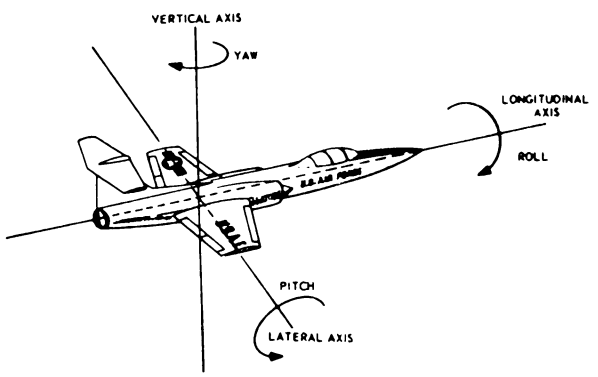

Figure 4-1. Aircraft maneuver axes.

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Yaw angle. The yaw, or heading, angle is the angle between the aircraft longitudinal axis and a north reference measured clockwise from the north reference in a horizontal plane. The heading angle may be any value from 0° through 360°, depending upon the heading of the aircraft and the north reference used (true, magnetic, or grid).

Attitude. The attitude of the aircraft is the position of the aircraft at any moment as determined by its inclination about its three axes. To define aircraft attitude fully, you must describe its pitch, roll, and heading.

Exercises (615):

1. What are the three orthogonal axes about which the aircraft moves?

2. What do we call the axis that runs fore and aft in the plane of symmetry (the axis about which the aircraft rolls)?

3. In what plane is the roll angle measured, and what is its maximum value?

4. In what direction is an aircraft flying when its pitch angle is +90°?

5. If the yaw angle of an aircraft is 180°, in what direction is the aircraft flying?

616. State the minimum number of gyroscopes and accelerometers required for a stable element and their relationship.

Components of the Stable Element. Generally, the stable element is made up of gyroscopes, accelerometers, and the synchronous devices necessary to control the gimbal orientation and to measure aircraft attitude.

The frame of reference in which this element is held stable consists of three orthogonal axes. Since a 2° gyroscope has two sensitive axes, we can use two gyroscopes in such a way as to sense motion about the three axes. Mounting the two gyroscopes with their sensitive axes mutually perpendicular makes the stable element sensitive to motion about the three orthogonal axes.

Generally, accelerometers are sensitive along one axis. Therefore, to sense latitude and longitude changes of the vehicle from the point of departure, we use two accelerometers with their sensitive axes aligned mutually perpendicular in a plane horizontal to the earth's surface. The output of the third accelerometer, which senses vertical motion, is not necessary in this system and therefore is not discussed. We mention it here because its output can be used by other avionics equipment. Figure 4-2 illustrates the orientation of the gyros and the accelerometers with respect to the coordinate axes of the frame of reference.

Exercises (616):

1. How many 2-degree-of-freedom gyroscopes are needed to establish the three orthogonal axes of our frame of reference?

2. What is the minimum number of accelerometers required by the INS to sense latitude and longitude changes?

3. How are the gyroscope axes mounted with respect to each other?

4. Which accelerometers have their axes aligned horizontally to the earth's surface?

617. State the purpose of components and operational techniques used in aligning and maintaining alignment of a stable element.

Orientation of the Stable Element. The heart of the inertial system is the stable element. It is physically oriented to the frame of reference. This orientation enables the system to sense motion within and measure attitude with respect to the frame of reference. The gimbal system, during an align phase, electronically

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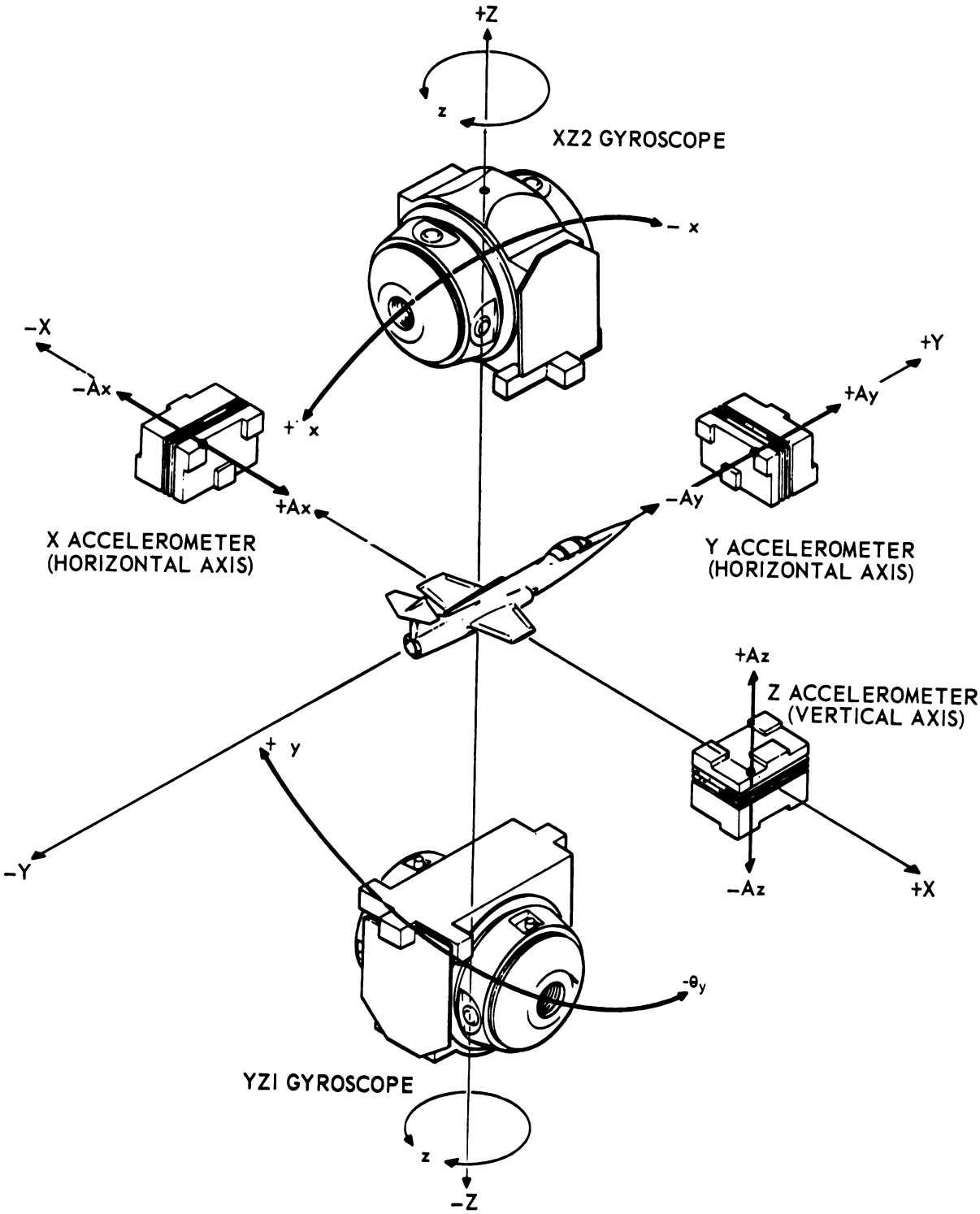

Figure 4-2. Location of gyros and accelerometers with respect to the coordinate axes.

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aligns the stable element to the local vertical and orients it to the frame of reference. The gimbal system uses a computed signal or signal outputs from the stable element components to do this alignment and orientation. Generally, the alignment is sequenced to—first, level the stable element or align it to the local vertical, and then second, orient the stable element to true north.

The gimbal drive system, by using the accelerometer output signals, levels the stable element. If the stable element is not aligned to the local vertical, the accelerometers—which normally sense only horizontal acceleration—feel a component of earth's gravity. The gimbal system uses the output signals from these accelerometers to precess the gyroscope spin axes to the horizontal. In turn, the system uses the gyroscope outputs to drive the platform gimbals to their proper orientation. Once the stable element is leveled, it must be oriented to the frame of reference by aligning the gyroscope spin axes to the north and east coordinate axes of the frame of reference. This may be accomplished by a computed or memory signal or by allowing the system to gyrocompass to its north reference. Gyrocompassing in this case is a procedure that uses accelerometer signals to align the system to its north reference. After the stable element is aligned to the frame of reference, this orientation must be maintained. A gyroscope is essentially a space reference—that is, it tends to remain oriented to a fixed point in space and moves in respect to the earth's surface. Consequently, in order to keep the gyroscopes oriented to the frame of reference, they must be moved or precessed to compensate for the rotation of the earth (earth rate) and for the movement of the aircraft over the surface of the earth (transport rate).

In early gyro systems, a short pendulum was used to sense gravity and thereby maintain the gyroscopes roughly oriented to local vertical. However, aircraft accelerations caused by maneuvers and disturbances upset the pendulum. Consequently, using a physical pendulum introduces undesirable errors in the system. Present gyroscopes are capable of very low random drift rates—that is, in the neighborhood of one hundredth of a degree per hour—which makes a highly accurate inertial guidance system possible. It is desirable to compute accurate torquing rates for gyroscope earth rate and transport rate compensation. In an inertial system, these torquing rates are calculated in a computer subsystem.

The computer must solve some trigonometric functions to obtain earth rate and transport rate torquing signals. In the following paragraphs, we show how these trigonometric functions are derived.

Exercises (617):

1. What system aligns the stable element during an alignment phase?

2. What are the two phases of the alignment sequence for a stable element?

3. If the stable element is not aligned, what component can feel earth gravity?

4. What mathematical functions are performed to solve for earth rate and transport rate corrections?

5. What components provide signals to align the system during gyrocompass?

6. How is the stable element alignment maintained?

618. Given the necessary input, compute the components of earth rate, transport rate, and total torque rates required to compensate for earth rate and transport.

Earth Rate and Transport Rate. Earlier in our text, we discussed earth rate and its effect upon the inertial sensing components. We said the earth rotated at 15° per hour. This is only a close approximation and is in fact what the 24-hour clock is based upon. However, these approximations are not accurate enough to calculate earth rate for the INS. The exact rotation of the earth is 15.04188° (0.26253 radians) per hour, based on the sidereal day of 23 hours 56 minutes and 04.09054 seconds. In inertial navigation, the 15.04188° per hour rotation is called *full earth rate* and its symbol is omega (Ω). To calculate the proper torquing rates for the gyros, you must break the full

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earth rate into horizontal and vertical components.

Full earth rate is broken into horizontal and vertical components and expressed as trigonometric functions of latitude (ϕ). You can see from figure 4-3 that the following relationships are true:

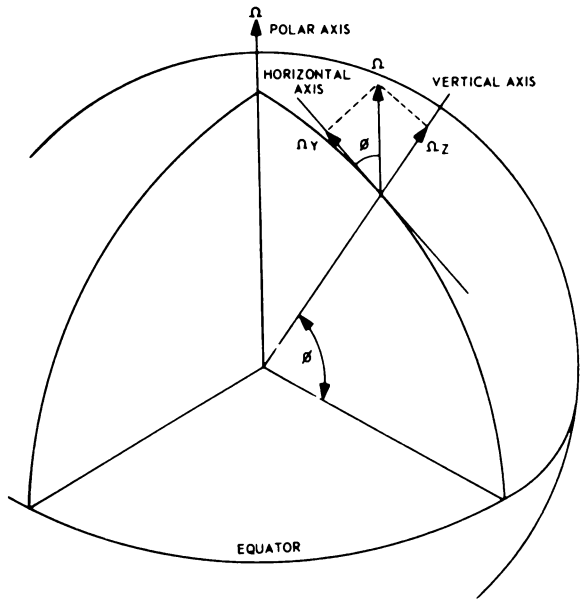

Figure 4-3. Horizontal and vertical components of earth rate.

$$\Omega y = \Omega \cos \phi$$
$$\Omega z = \Omega \sin \phi$$

where

Ωy = horizontal component of earth rate
Ωz = vertical component of earth rate
Ω = full earth rate
ϕ = angle of latitude

The horizontal component vector of earth rate is coincident with the north-south axis of the frame of reference. Also, the vertical component vector of earth rate is coincident with the vertical axis of the frame of reference. Therefore, a signal representing the vertical component of earth rate (Ωz) is required to torque the gyroscopes about the vertical axes. Also a signal representing the horizontal component of earth rate (Ωy) is required to torque the gyroscopes about the horizontal axis or the north-south axis.

Transport rate torquing causes the gyroscopes to precess about the north-south, east-west, and vertical axes of the frame of reference. Transport rate torquing depends upon the velocity of the aircraft in respect to the frame of reference. As shown in figure 4-4,

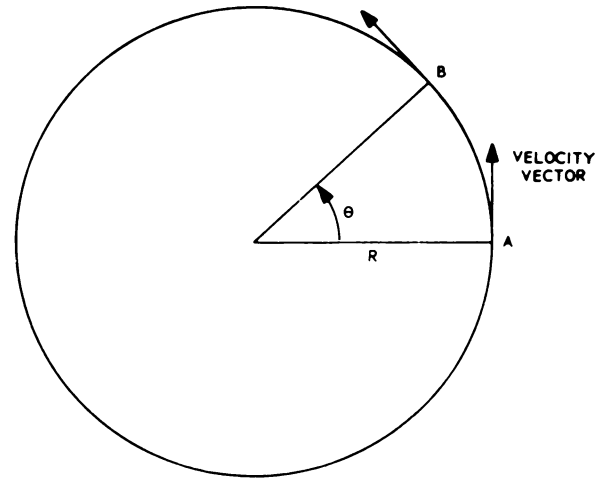

Figure 4-4. Angular velocities.

the angle that is subtended at the center of a circle is directional proportional to the arc A-B. This angle is represented by the symbol θ (theta). If an aircraft moves from A to B in unit time, the angular rate, ω (omega), is directional proportional to the linear velocity of the aircraft along the periphery of the circle. Or

$$\omega = \frac{V}{R}$$

where

ω = angular velocity in radians/hour
V = Linear velocity in miles/hour
R = radius of the circle in miles

Remember:

$$\text{A radian} = \frac{\theta \text{ (in degrees)}}{180°}$$

Since the velocity vector is perpendicular to the radius at all times, it has the same angular velocity about an axis perpendicular to the plane of the circle. As the aircraft moves over the surface of the earth, the platform must be precessed about the east-west and north-south axes commensurate with the component velocities. That is, the velocities used to determine the transport torquing rates are the north-south and east-west velocities. These compo-

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nent velocities may be determined by the following relationships:

$$Vy = Vg \cos \theta t$$

$$Vx = Vg \sin \theta t$$

where

Vy = north-south componnent velocity

Vg = aircraft ground velocity

θ t = aircraft true heading

Vx = east-west component velocity

The east-west velocity is used to determine the rate at which the platform is rotated about the north-south axis, and the north-south velocity is used to determine the rate of rotation about the east-west axis. As shown in figure 4-5. these rates are as follows:

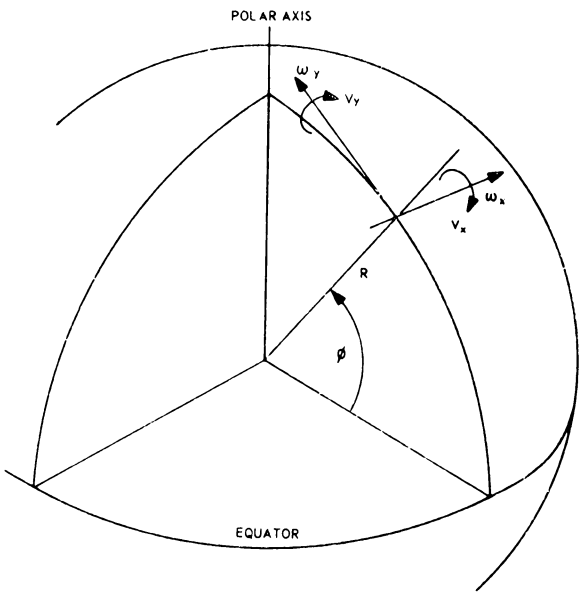

Figure 4-5. Horizontal axes transport rate terms.

$$\omega y = \frac{Vx}{R}$$

$$\omega x = \frac{Vy}{R}$$

where

ω y = rate of rotation about the north-south axis

Vx = east-west velocity (accelerometer output)

R = radius of the earth (3,959 miles)

ω x = rate of rotation about the east-west axis

Vy = north-south velocity (accelerometer output)

In order to maintain the stable element oriented to the north reference, the element must rotate about the vertical axis to compensate for east-west velocity. In this case, the center of rotation is a point in space that is the intersection of the polar axis and the north-south axis of the platform, as shown in figure 4-6. The radius, therefore, is the distance from the point of intersection to the stable element.

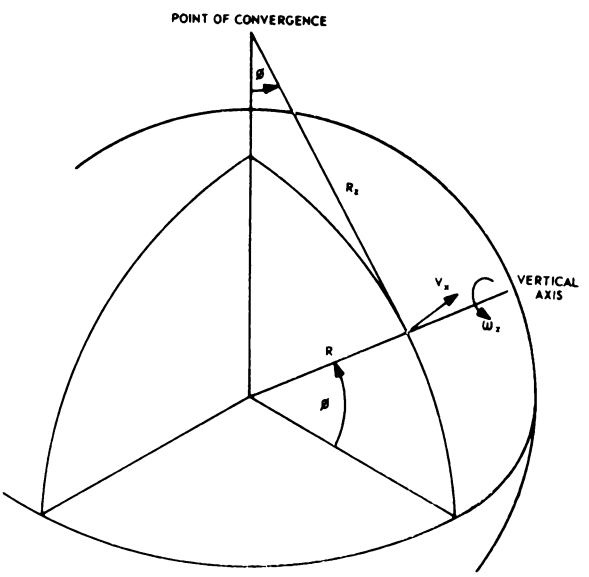

Figure 4-6. Vertical axes transport rate terms.

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The rate of rotation is

$$\omega z = \frac{Vx}{Rz}$$

where

ωz = rate of rotation about the vertical axis

Vx = east-west velocity

Rz = distance from stable element vertical axis to the intersection of the polar axis and the north-south coordinate axis

Rz may be expressed in terms of earth radius and the angle of latitude by the following relationship:

$$Rz = \frac{R}{\tan \phi}$$

therefore

$$\omega z = \frac{Vx}{R} \tan \phi$$

The total rates of rotation about the coordinate axes are the sums of the earth rates and transport rates, or

$$\omega y = \Omega \cos \phi + \frac{Vx}{R}$$

$$\omega x = \frac{Vy}{R}$$

$$\omega z = \Omega \sin \phi + \frac{Vx}{R} \tan \phi$$

Exercises (618):

1. At what rate (degrees per hour) will an INS on the Equator require the platform to be torqued about the north-south and vertical axes to compensate for earth rate?

2. At a particular instant an aircraft using INS is directly over the Equator flying due north at 395.9 miles per hour. (For this problem omit any altitude corrections, these will be discussed later.) Compute the total torque rates required to compensate for earth rate and transport rate.

3. What effect would an increase in the value of Rz have on the rate of rotation about the vertical axis (ωz)?

4. Which axis does not have an earth rate component (Ω) applied?

5. What axis has a latitude correction (ϕ) applied to transport rate and earth rate?

6. Which velocity is used to determine the rate at which the platform is rotated about the north-south axis?

4-2. Four-Gimbal System

To achieve a highly accurate inertial navigation system, it is necessary that the inertial components such as gyroscopes and accelerometers be precise and accurate. Since the platform integrates the inertial components and couples them to the rest of the inertial system, it is equally important that the platform be of high-quality. The platform we discuss is a rugged and reliable mechanism that allows the attributes of the inertial components to be realized.

619. State the quantity required and describe the arrangement of the components of a four-gimbal stable platform system.

Description. The platform is a four-gimbal program that uses two 2-degree-of-freedom gyroscopes and three nonintegrating accelerometers. The stable element is located in the center of the platform gimbals. Figure 4-7 is a phantom view of the stable element showing its configuration. Since the stable element has 360° of freedom about a vertical axis in respect

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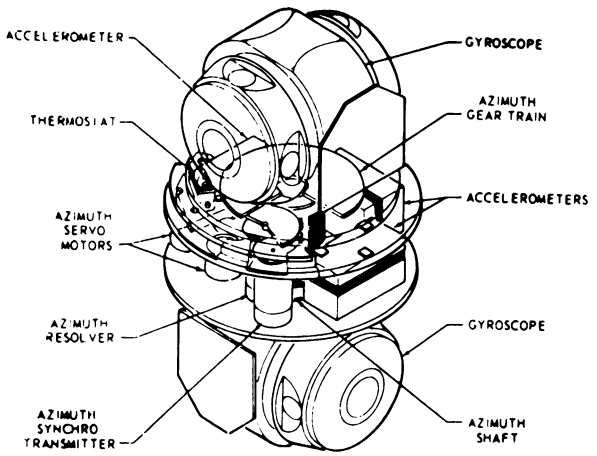

Figure 4-7. Phantom view of the stable element.

to the platform, it is also the azimuth gimbal. The gyros are mounted in a "dumbbell" configuration with one gyro on the top and one gyro on the bottom of the azimuth structure. The spin axes of the gyroscopes are in a horizontal plane and perpendicular to each other. Figure 4-8 is a plane view of the platform and shows the relative location of the components.

The three accelerometers are mounted on the azimuth gimbal structure, each with its sensitive axis coincident with a coordinate axis. Also mounted on the azimuth gimbal are the azimuth gimbal servomotors, the azimuth synchro control transmitter, and the azimuth resolver.

The azimuth gimbal is mounted on the inner roll gimbal. The inner roll gimbal has a limited magnitude of freedom—that is, it moves only approximately $\pm 18°$ in respect to the pitch gimbal. This in one synchro control transmitter between the inner roll gimbal and the pitch gimbal on which the inner roll gimbal is mounted.

The pitch gimbal has full freedom—that is, 360° in respect to the platform. Mounted on the pitch gimbal are two servomotors that drive the inner roll gimbal. Two synchro control transmitters are mounted between the pitch gimbal and the outer roll gimbal.

The outer roll gimbal is supported by the front and rear platform mounts. There are two servomotors on the outer roll gimbal that drive the pitch gimbal. Two synchro control transmitters are mounted betweem the outer roll gimbal and the gimbal mounts. The outer roll gimbal servomotors are on the front gimbal mount.

Exercises (619):

1. How many gyros are used in a four-gimbal system?

2. Describe the configuration of the gyros in relation to each other.

3. Name the gimbals in order beginning from the center.

4. Describe the movement of the azimuth, inner roll, and pitch gimbals.

620. Given a list of functions, match each with the component of a four-gimbal system that performs it.

Theory of Operation. During alignment, the stable element is leveled and oriented to the frame of reference. While the system is operating, the orientation of the stable element is maintained by the computed torquing signals applied to the gyroscopes. These torquing signals are computed from earth rate and transport rate which cause the gyroscopes to precess about their horizontal and vertical axes and hold the gyroscopes oriented to the frame of reference. The platform gimbals allow the aircraft to move without disturbing the orientation of the stable element. In order to preclude aircraft angular motion and disturbances from upsetting the stable element, the platform gimbals are driven by the servomotors according to signals from the gyroscopes and the inner roll gimbals. Four servoloops control the gimbal orientation.

The four-gimbal configuration is used so that the aircraft may perform any maneuver without disturbing or tumbling the stable element. If only three gimbals were used, aircraft maneuvers could cause gimbal lock. Gimbal lock is a condition in a three-gimbal system in which the axes of any two gimbals coincide, thus causing a loss of a degree of

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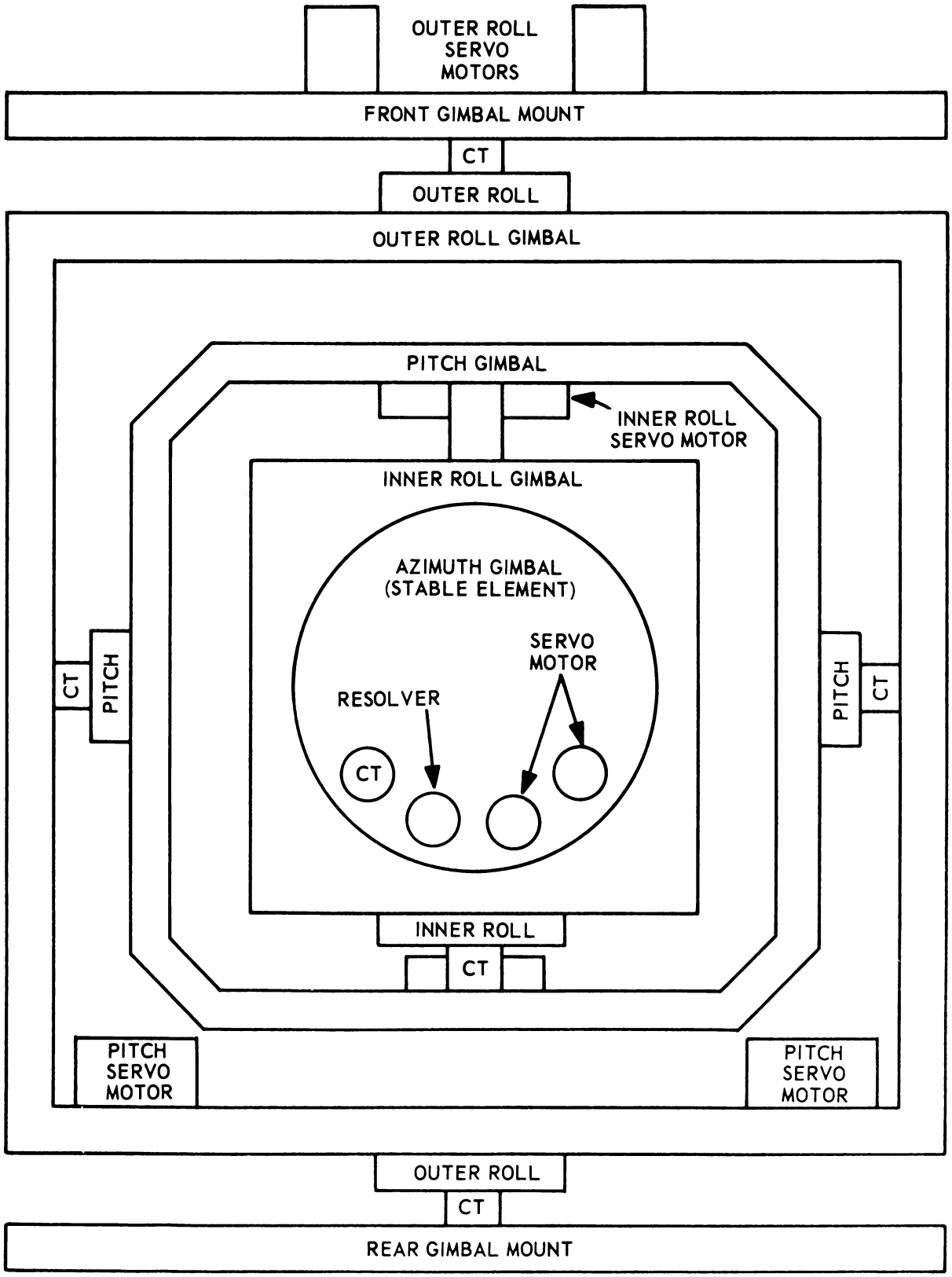

Figure 4-8. Plane view of the platform.

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freedom. (Gimbal lock will probably cause the stable element to tumble.)

During an Immelmann turn or any aircraft maneuver during which the aircraft approaches or passes through the vertical, the outer roll gimbal is flipped. Flipping is the rotation of the outer roll gimbal through the required angle to maintain the azimuth gimbal and pitch gimbal axes perpendicular. When the outer roll gimbal flips, attitude signals from the platform will exactly present the aircraft attitude. If the outer roll gimbal did not flip, after a half-loop and half-roll maneuver of the aircraft, heading and roll attitude signals would be 180° out of phase. Attitude ambiguity is therefore precluded by the gimbal's flipping. Also, since the

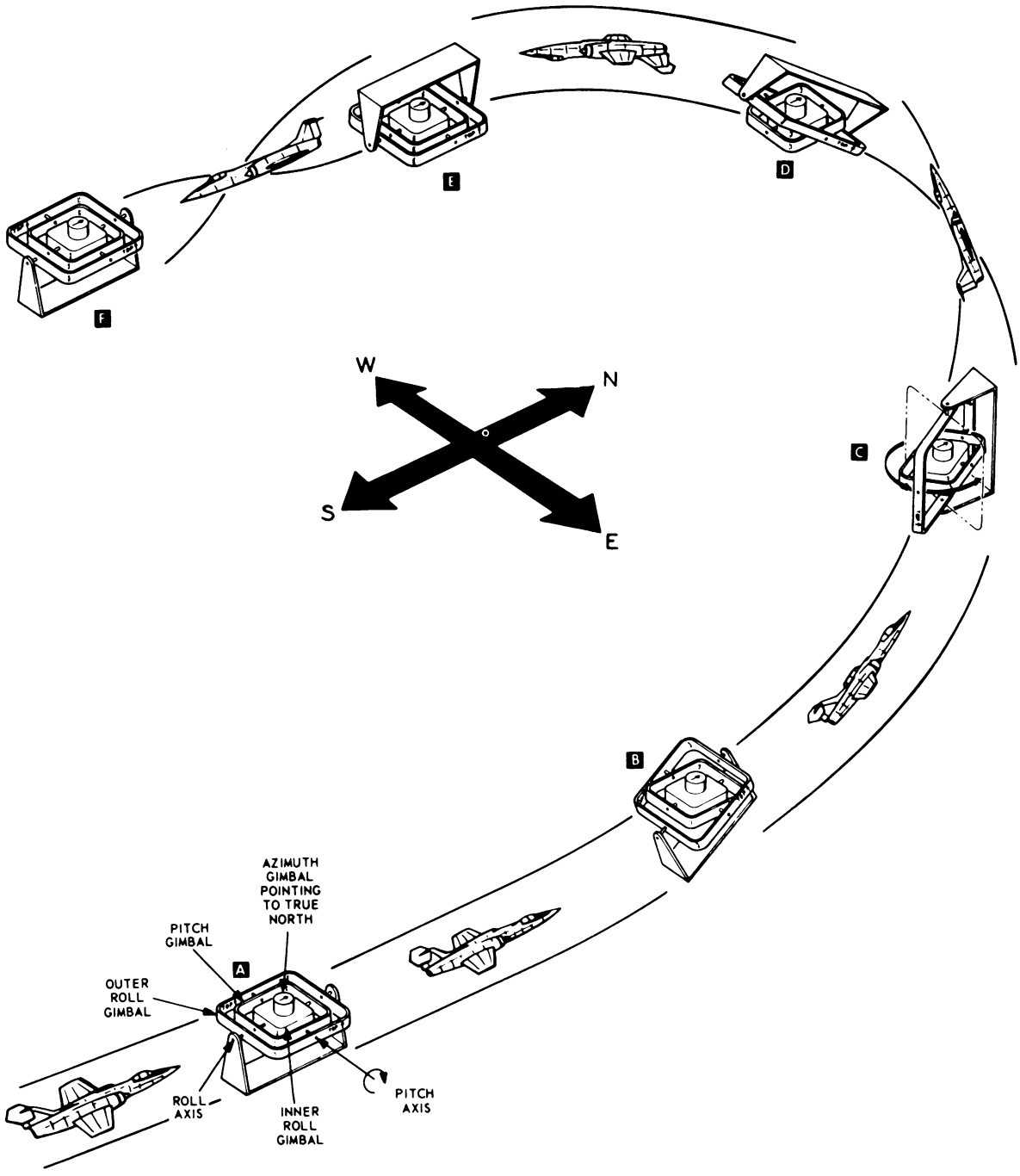

Figure 4-9. Gimbal flipping action.

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outer roll gimbal is flipped, the magnitude of freedom of the inner roll gimbal may be limited.

Figure 4-9 illustrates gimbal flipping action. In figure 4-9,A, the aircraft is flying level, due north. The stable element (azimuth gimbal) is aligned to true north. Note the alignment of all the gimbals. As the aircraft starts to climb with a slight roll, note the movement of the pitch and outer roll gimbals in figure 4-9,B. Figure 4-9,C, shows the position of the gimbals when the aircraft is flying straight up (+90°) and has rolled approximately 90° counterclockwise. The pitch gimbal is displaced almost 90° from its position in figure 4-9,A. Figure 4-9,D, shows the position of the gimbals as the aircraft begins to flip and fly south. Figure 4-9,E, shows the gimbal alignment as the aircraft flies inverted. Figure 4-9,F, shows the aircraft again flying right side up and flying south.

Each platform gimbal (fig. 4-9) has a definite orientation. This orientation is required to isolate the stable element from disturbances caused by aircraft maneuvers, to hold the stable element oriented, and to measure aircraft attitude. As we discuss the orientation of each gimbal, locate it in figure 4-9,A. Then, note its movement during the aircraft maneuver in the remaining sequence of pictures. First look at the azimuth gimbal (stable element) that is oriented to the frame of reference. Note that its axis is always vertical. The inner roll gimbal and its axis must be horizontal in order to keep the azimuth gimbal axis vertical. Note how the inner roll gimbal axis follows the aircraft heading. The pitch gimbal and its axis must be horizontal at all times in order to keep the inner roll axis horizontal. Note that the pitch gimbal axis follows a horizontal projection of the aircraft lateral axis. The outer roll gimbal must maintain the pitch gimbal axis in a horizontal plane. To do this, the outer roll gimbal axis remains parallel to the aircraft longitudinal axis and follows the aircraft heading. While the system is operating, the azimuth gimbal, inner roll gimbal, and the pitch gimbal are always horizontal and are commanded by signals originating at the gyroscope pickoff coils. The outer roll gimbal is commanded by a synchro control transmitter measuring the angle between the inner roll gimbal and the pitch gimbal.

In the stable element (fig. 4-7), the spin axis of the top gyroscope is coincident with the north-south coordinate axis and is sensitive to motion about the east-west and vertical axes. The spin axis of the bottom gyroscope is coincident with the east-west coordinate axis and is sensitive to motion about the north-south and vertical axes. There is, therefore, a redundant sensitivity about the vertical axis. Consequently, the top gyro is caged to itself about the vertical axis so that it cannot drift or be driven against the stops and cause the platform to tumble.

Gyroscope sensing. The azimuth resolver must translate the displacement of the stable element about the north-south, east-west, and vertical axes into pitch, roll, and azimuth gimbal torque signals. The aircraft maneuvers may be considered as separate pitch, roll, and turn motions; and the effect on gyroscopes may be reduced to sensing about the north-south, east-west, and vertical axes. These aircraft maneuvers tend to displace the stable element. As the displacement is sensed by the gyroscopes, the platform is torqued or driven in the opposite direction at an equal rate to prevent upset of the stable element.

The total gyroscope sensing is the sum of the individual sensing for roll, elevation (pitch), and turn (azimuth); that is,

$$\omega y = \omega r \cos a \cos \theta t - \omega p \sin \theta t$$

$$\omega x = \omega r \cos a \sin \theta t + \omega p \cos \theta t$$

$$\omega z = \omega az - \omega r \sin a$$

where

θt = aircraft true heading

ωr = roll rate vector of the aircraft

ωp = elevation or pitch rate vector of the aircraft

ωaz = turn rate vector of the aircraft

ωy = gyro sensing about the north-south coordinate axis

ωx = gyro sensing about the east-west coordinate axis

ωz = gyro sensing about the vertical coordinate

a = mechanical shaft angle

These are the total quantities sensed by the gyroscopes. These signals, which indicate that the stable element is being displaced, are used to torque the platform gimbals. The sensing about the vertical axis (ωz) is applied directly

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to the azimuth gimbal. The sensing about the horizontal axes (ωy and ωx) must be translated to roll and elevation by the azimuth resolver. The inputs to the azimuth resolver are true heading (θt), the gyroscope sensing about the north-south axis (ωy), and the gyroscope sensing about the east-west axis (ωx).

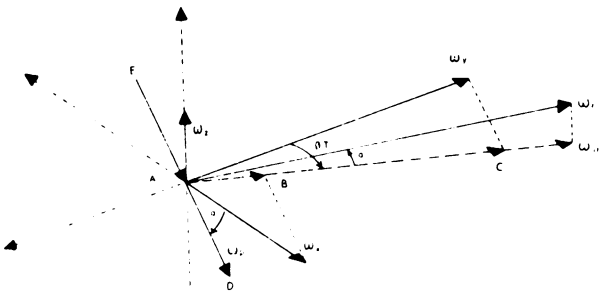

Figure 4-10. Gimbal torquing rates.

Gimbal torquing rates. Figure 4-10 shows how the vector quantities are used to determine gimbal torquing rates.
Assume

ωr = torquing rate of outer roll gimbal

ωir = torquing rate of inner roll gimbal

ωp = torquing rate of elevation gimbal

ωaz = torquing rate of azimuth gimbal

The azimuth gimbal torquing is as follows:

$$\omega az = \omega z$$

The inner roll gimbal torquing is as follows:

$$\omega ir = AB + AC$$

$$\omega ir = \omega y \cos \theta t + \omega x \sin \theta t$$

The elevation gimbal torquing is as follows:

$$\omega p = AD + EA$$

$$\omega p = \omega x \cos \theta t - \omega y \sin \theta t$$

The inner roll gimbal and pitch gimbal torquing signals fit the general equations for a resolver; that is,

$$Eo1 = Ei1 \cos a + Ei2 \sin a$$

$$Eo2 = Ei2 \cos a - Ei1 \sin a$$

where

Eo1 = first output of resolver

Eo2 = first input to resolver

Ei1 = second input to resolver

a = mechanical shaft angle

and

$$Eo1 = \omega ir$$

$$Eo2 = \omega p$$

$$Ei1 = \omega y$$

$$Ei2 = \omega x$$

$$a = \theta t$$

Figures 4-8 and 4-9 will aid you in understanding this paragraph. The orientation of the outer roll gimbal is determined by the inner roll gimbal synchro control transmitter. The outer roll gimbal must maintain the pitch gimbal axis in a horizontal plane, or perpendicular to the azimuth gimbal axis. Any deviation from this orientation changes the angle between the inner roll gimbal and the pitch gimbal. The inner roll synchro control transmitter senses this change and generates a signal whose amplitude and phase are determined by the amount and direction of the change. This signal is applied to the outer roll gimbal servo. Since the inner roll gimbal rate is a projection on a horizontal plane of the outer roll gimbal rate, the following relationship exists:

$$\omega ir = \omega r \cos a$$

or

$$\omega r = \omega ir \sec a$$

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where

ωir = projection of ωr on the horizontal plane

Consequently, the inner roll synchro control transmitter signal must be amplified as the secant of the elevation angle to maintain the two roll gimbals in coincidence.

Determining aircraft attitude. The attitude of the aircraft is determined by measuring angles between the platform gimbals. Azimuth or heading is measured between the azimuth gimbal (the stable element) and the inner roll gimbal. This is possible because the azimuth gimbal is oriented to the north reference of the frame of reference and the inner roll gimbal axis follows a horizontal projection of the aircraft's longitudinal axis. The pitch gimbal and its axis are horizontal, and the outer roll gimbal axis follows the longitudinal axis of the aircraft; therefore, the pitch, or elevation, angle is measured between the pitch gimbal and the outer roll gimbal. The roll angle is measured between the outer roll gimbal mount and the outer roll gimbal. The angle between the outer roll gimbal and the gimbal mount represents aircraft roll, because the outer roll gimbal axis follows the aircraft longitudinal axis and the pitch gimbal axis is always horizontal.

Exercise (620)

1. Match each function in column A with the appropriate component listed in column B. Each component may be used more than once or not at all.

Column A	Column B
1. Axis is always vertical.	a. Inner roll gimbal.
2. Axis follows aircraft heading.	b. Azimuth gimbal.
3. Axis follows aircraft laterial axis.	c. Pitch gimbal.
4. Flips during an Immelmann turn.	d. Outer roll gimgimbal.
5. Commanded by synchro between inner roll and pitch gimbal.	e. Top gyro.
6. Caged to itself about the vertical axis.	f. Bottom gyro.
7. Translates aircraft movement into pitch, roll, and azimuth torquing signals.	g. Azimuth resolver.
8. Allow movement of the aircraft without disturbing the stable element of the gyro.	h. True heading.
9. Allows any maneuver of an aircraft without tumbling.	i. Resolver inputs.
10. True heading, θt.	j. A four-gimbal configuration.

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Inertial Navigation System and Avionics Tie-In

IN THE PRECEDING chapters of this volume, you learned about the general principles of inertial navigation. In the remaining chapters, you will study a typical airborne inertial navigation set to see how these principles work in practice. We call it the inertial navigator—not because it is the only one in existence but because it best typifies those in general use. Get to know this set well.

5-1. General Description of the System

The inertial navigator is a lightweight, automatic, self-contained navigation set that can give accurate navigation information without external references. When properly aligned, the system continuously provides:

a. Aircraft position in the form of X- and Y-coordinates of displacement from the point of flight origin.

b. Inertial true heading.

c. Attitude of the aircraft about its three major axes.

d. Accelerations and velocities along the major axes.

The inertial navigator has no readout devices of its own. The information it develops is routed to associated avionics equipment that can make the best use of the information. For example, attitude information is passed on to the aircraft attitude indicator and to the autopilot. Position information is fed to a computer where it is displayed in terms of the aircraft's present latitude and longitude.

The inertial navigator is comprised of four components: the gyro stabilized platform, inertial navigator computer, inertial navigator control, and inertial navigator output signal distribution unit (OSDU). Refer to foldout 1 (in the separate inclosure to this volume) while we discuss the function of these components and their tie-in with each other and the associated avionics equipment. Find each component and unit as we discuss its function. Do not be overly concerned at this time with the signals that appear on the foldout. Their development will become apparent when you study signal flow in the system.

621. Relate given components and subsystems to the appropriate major unit of a typical inertial navigational system.

The Gyro Stabilized Platform. The gyro stabilized platform (which we will also call the inertial stabilized platform, inertial platform, or just platform) consists of a stable element cradled within four gimbals, the gimbals themselves, and the supporting structure. On occasions we will use the term "platform" loosely, to mean only the stable element.

The four gimbals, listed from the outermost inward, are: outer roll, pitch, inner roll, and azimuth. The stable element inside the azimuth gimbal is a roughly dumbbell-shaped structure with a gyroscope mounted at each end. When the system is readied for operation, the stable element is brought into operating position (the longitudinal axis of the stable element aligned with the local vertical, the spin axes of both gyros horizontal and oriented to grid north). This process, *alignment,* is performed in the stationary aircraft before takeoff. After the stable element is aligned, it tends to retain its orientation in space. It is purposely tilted to the earth as the aircraft travels about over the surface of the earth.

The platform mounts three accelerometers with their sensitive axes mutually perpendicular. When the stable element is aligned properly, the Y-accelerometer senses accelerations in the north-south direction. The X-accelerometer senses accelerations in the east-west direction, and the Z-accelerometer senses accelerations along the local vertical.

All movements of the aircraft are sensed in their entirety by measuring their components along the X-, Y-, and Z-axes. For this reason, the position of the aircraft in space is expressed solely in terms of the X-, Y-, and Z-axes, these being the major axes of both the aircraft and the stable plane.

Inertial Navigation Computer. The inertial navigator computer, which we will call simply "the computer," is comprised of three subsystems: platform electronics, navigation computer, and power supply.

Platform electronics subsystem. Go/no-go circuits that monitor critical signals of the inertial navigation system are part of the platform electronics subsystem. This subsystem also includes sets of servoamplifiers for positioning the platform gimbals and for restoring the three accelerometers. In addition, a separate servoamplifier cages the upper gyro to its own azimuth output.

Navigation computer subsystem. The function of the navigation computer subsystem is to develop, in electronic form, the equations used to calculate velocity and position. Also, this subsystem supplies the torquing currents that maintain the gyros in correct orientation. Its major servoloops are acceleration (X, Y, and Z),

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velocity (X and Y), position (latitude and longitude), and gyro torquing (X, Y, and Z).

Power supply subsystem. The power supply subsystem provides the operating voltages for the inertial navigation system. The primary power requirements for operation of the INS are:

- 115 ± 7.5 VAC,400 ± 20 Hz, 3 phase at 750 VA per phase
- +28 VDC

The power supply voltage outputs are:

- +30 VDC regulated and −30 VDC regulated
- +28 VDC filtered and unfiltered
- Precision +10 VDC and precision −10 VDC
- 5.8 VAC, 6.3 VAC, 12.6 VAC, and 140 VAC at 400 Hz
- Precision frequency gyro spin motor voltage (90 VAC at 375 Hz)
- Precision 15 VAC at 4.5 kHz
- 115 VAC at 4.5 kHz

The Inertial Navigation Control. This unit is used to select the system's modes of operation—off, standby, align, and navigate.

Inertial Navigation Output Signal Distribution Unit (OSDU). The inertial navigator OSDU serves as source of roll, pitch, and azimuth information for the associated avionics equipment in the aircraft. Roll and pitch signals are routed through the unit via appropriate leads, and azimuth signals are derived from a followup servo within the unit. The OSDU also incloses an air valve servo that regulates the cooling airflow through the cover of the platform.

Exercises (621):

Match each of the components or subsystems in column A with its major unit or a typical inertial navigation system in column B.

Column A	*Column B*
____ 1. Gyros and accelerometers.	a. Inertial navigation computer.
____ 2. Platform electronics subsystem.	b. Platform.
____ 3. Navigation computer subsystem.	c. Inertial navigation output signal distribution unit.
____ 4. Power supply subsystem.	d. Inertial navigation control.
____ 5. Selects mode of operation.	
____ 6. Air valve servo.	
____ 7. Followup servo.	
____ 8. Go/no-go circuits.	

622. Identify important system characteristics.

Characteristics. Listed in table 5-1 are the range of operation, maximum angular rates, output signal accuracy, and temperature tolerances of the inertial navigation system (INS). Table 5-1 contains information required by aircrew member and maintenance personnel. The aircrew is concerned with the navigation accuracy of the system so that they may identify substandard operation or an out of tolerance condition. Maintenance personnel need to know the system accuracy and other system characteristics, such as the gyro drift rate tolerance or circular error probability, because these are some of the items that will be checked during an operational check or bench check to determine the status of the system or a component.

Exercises (622):

1. What is the circular error probability for a rapid align?

2. What is the drift accuracy of the gyros?

5-2. Avionic Tie-In

In this section, you will learn the specifics of the inputs and outputs of the INS to and from typical related aircraft systems.

623. Identify given signals on an INS avionics tie-in diagram as inputs or outputs to specified units, and state important characteristics of selected signals.

Pitch, roll, and true heading signals from the OSDU (see right side of fig. 5-1) are supplied through a relay panel to the flight director group and the attitude reference combining computer system. Pitch and roll are also applied through the relay panel to the fire control system. In addition, east-west and north-south velocity, true heading, and variation information are supplied by the OSDU to an amplifier-computer in the navigational computer system. Latitude and longitude and air data mode control signals are supplied by the navigator computer to an amplifier-computer in the navigational computer system. A best available true heading signal is supplied by a computer control assembly in the navigational computer system to the OSDU until the System enters Gc. BATH is a combination of magnetic heading (from a compass adapter compensator in the attitude reference bombing computer system) and magnetic variation from the navigational computer system. A barometric altitude signal is supplied by the air data computer to the Vx integrator in the navigator computer for increasing the longitude rate for a given velocity at higher altitudes. In addition, the navigator computer applies an inertial no-go signal to the aircraft warning lights (INERTIAL NAV SYS OUT), indicating the aircraft power has been removed from the INS because certain voltage tolerances in the INS have been exceeded.

The INS can be adapted for use in reconnaissance aircraft. When adapted for reconnaissance use, the system provides the outputs previously explained plus altitude above terrain, groundtrack steering, groundspeed, drift angle, groundspeed above terrain ratio, vertical attack angle, vertical velocity, and climb angle.

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TABLE 5–1
SYSTEM CHARACTERISTICS

FUNCTION	TEMPERATURE	RANGE	MAXIMUM RATE	ACCURACY
Accelerometers	160 ± 2°	0 to 20 gs	N/A	N/A
Gyros	160± 2°	N/A	N/A	Drift .01 ° per hour
Platform	128 ± 5°	N/A	N/A	N/A
Component Oven	158 ± 4°	N/A	N/A	N/A
Navigation	N/A	Over 4000 NM	N/A	*3 NM/hr (normal align) CEP *5.5 NM/hr (rapid align) CEP
Aircraft Pitch	N/A	0 to 360 °	40°/sec 80 to 100° 60°/sec all other	15 min of arc rms
Aircraft roll	N/A	0 to 360°	300°/sec	15 min of arc rms
Aircraft yaw	N/A	0 to 360 °	50°/sec	N/A
Heading	N/A	0 to 360°	N/A	18 min of arc rms

*Circular error probability (CEP) accuracies apply to latitudes between 75° north and 75° south.

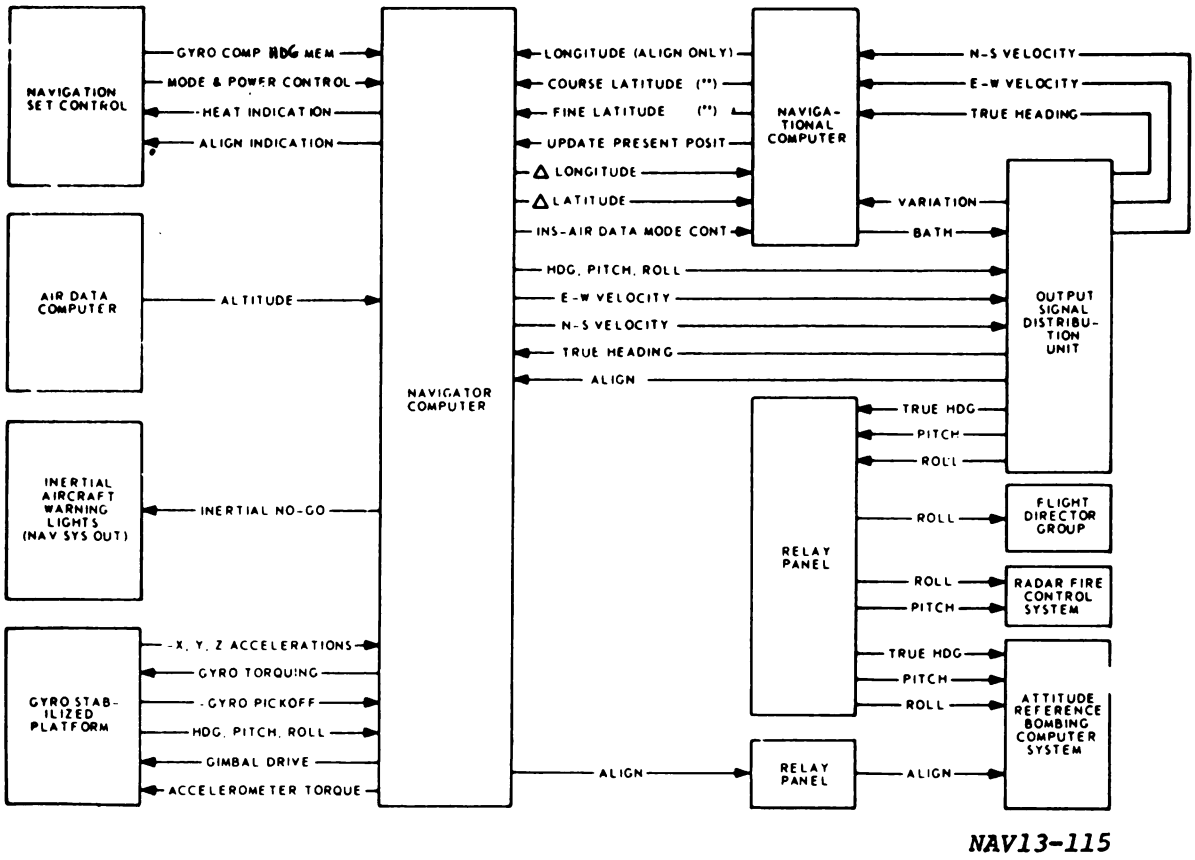

Figure 5–1. INS avionics tie-in.

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Exercises (623):

For questions 1 though 7, use figure 5-1 to match the signal identified in column A below with the unit shown in column B, by placing the letter of the signal in the appropriate space.

Column A (Signal)	*Column B (Unit)*
____ 1. Accelerometer torque input.	a. Navigation set control.
____ 2. Altitude output.	b. Navigator computer.
____ 3. Gyro compass heading memory output.	c. Gyro stabilized platform.
____ 4. Update present position input.	d. Output signal distribution unit.
____ 5. N–S velocity input.	e. Navigational computer.
____ 6. Align, true heading, pitch, and roll input.	f. Air data computer.
____ 7. True heading output.	g. Attitude reference bombing computer system.

8. How long is BATH available during align?

9. What computation in the navigator computer is affected by barometric attitude?

10. List, in order, the units that pitch and roll signals must go through to get from the platform to the fire control system.

5-3. Power Supplies Block Diagram

Power requirements for the INS are developed by two power supplies. The primary power supply assembly, 3A25, is located within the navigator computer. A smaller power supply is located in the OSDU. Input power, 115 VAC, 400 Hz, 3 ϕ is provided by the aircraft power system. Refer to the block diagram in figure 5-2 as you study the power supplies.

624. Using a simplified block diagram of a power supply, trace the inputs and outputs.

Computer Power Supply. Phases A and B of the aircraft power are routed through the primary power control circuits for ambient heater, upper-lower gyro heater, and air valve servo power (upper left of fig. 5-2). Three-phase 115-VAC aircraft power is applied through the control circuits and filter 3A25FL1 to transformer 3A25T6. The outputs of T6, stepped-down voltages, are applied to three 3-phase full-wave rectifiers.

The output of 3-phase full-wave rectifier No. 1 is +45 VDC. This voltage is applied to a regulator which provides the +30 VDC regulated for the transistor bias line, the precision ± 10-VDC regulator, the 3-kHz frequency generator, and the primary power control circuits.

The output of 3-phase full-wave rectifier No. 2 is +15 VDC unregulated and −30 VDC regulated. The −30 VDC regulated is applied to the transistor bias line and the precision ±10-VDC regulator.

The output of 3-phase full-wave rectifier No. 3 is +28 VDC. This voltage is used by the voltage monitor circuits and relays throughout the system. The precision ±10-VDC regulator uses the +30 and −30 VDC to develop the ± VDC used by the system for reference and bias voltages.

Phases A and B of the aircraft power are applied to transformer 3A25T4. Transformer T4 provides 5.8 VAC 400 Hz as antibacklash voltage for servos; 12.6 VAC 400 Hz for modulator reference, and a stepped-down output to a rectifier network. The rectifier network output is +28 VDC unfiltered, which is used for relays throughout the system.

A, B, and C phases of the aircraft power are applied to a rectifier and dropping resistor section. The output of this section is +28 VDC, which energizes A3K22 when the mode selector switch is set to STBY. B and C phases of the aircraft power are applied to transformer 3A25T5. The output of T5 is 6.3 VAC 400 Hz, which is used as excitation voltage for the vibrators.

The 3-kHz frequency generator or tuning fork is excited by the regulated +30 VDC with the output applied to a frequency divider, whose output is 1.5 kHz. This signal is applied to a third harmonic frequency generator and to a second frequency divider. The output of the third harmonic generator is 4.5 kHz, and is applied through two amplifiers to transformer 3A25T1. T1 has two outputs, 15 VAC 4.5 kHz, which is used for reference in the system and 115 VAC 4.5 kHz, which is used for AC synchro excitation in the system. The output of the second frequency divider, 375 Hz, is amplified and applied to 3A20T1. The secondary of T1 is a 90° phase shifter; its outputs are 90° apart. Each of the two outputs is applied to a paraphase converter. The converter outputs, 180° apart, are amplified and applied to Scott-T connected transformers 3A25T2 and 3A25T3, which will be explained later in this volume. Outputs of the transformers are 90 VAC, 375 Hz, A, B, and C phases. These three outputs are the sustaining voltages applied through K1 and K2 to the gyro spin motors in fine align (Af) and gyrocompass (Gc) submodes, and in navigate (NAV) mode.

A, B, and C phases from the primary power control circuits are also applied to 3A25-FL1 and 3A25T6 located at the bottom-center section of figure 5-2. (Note that this is part of FL1 and T6 above). The outputs of T6 are 175 VAC, 400 Hz, A, B, and C phases, which are applied as run-up voltages to the gyro spin motors in coarse align (Ac) submode.

OSDU Power Supply. (Lower left corner of figure 5-2.) Aircraft 115V, 400 Hz, 3-phase power is applied to OSDU transformer T1. One output of the transformer is rectified unfiltered +30 VDC. Other outputs of the transformer are 13V, 0° and 90°; 22V, 0°; 26V, 90°; and 6.3V, 75°.

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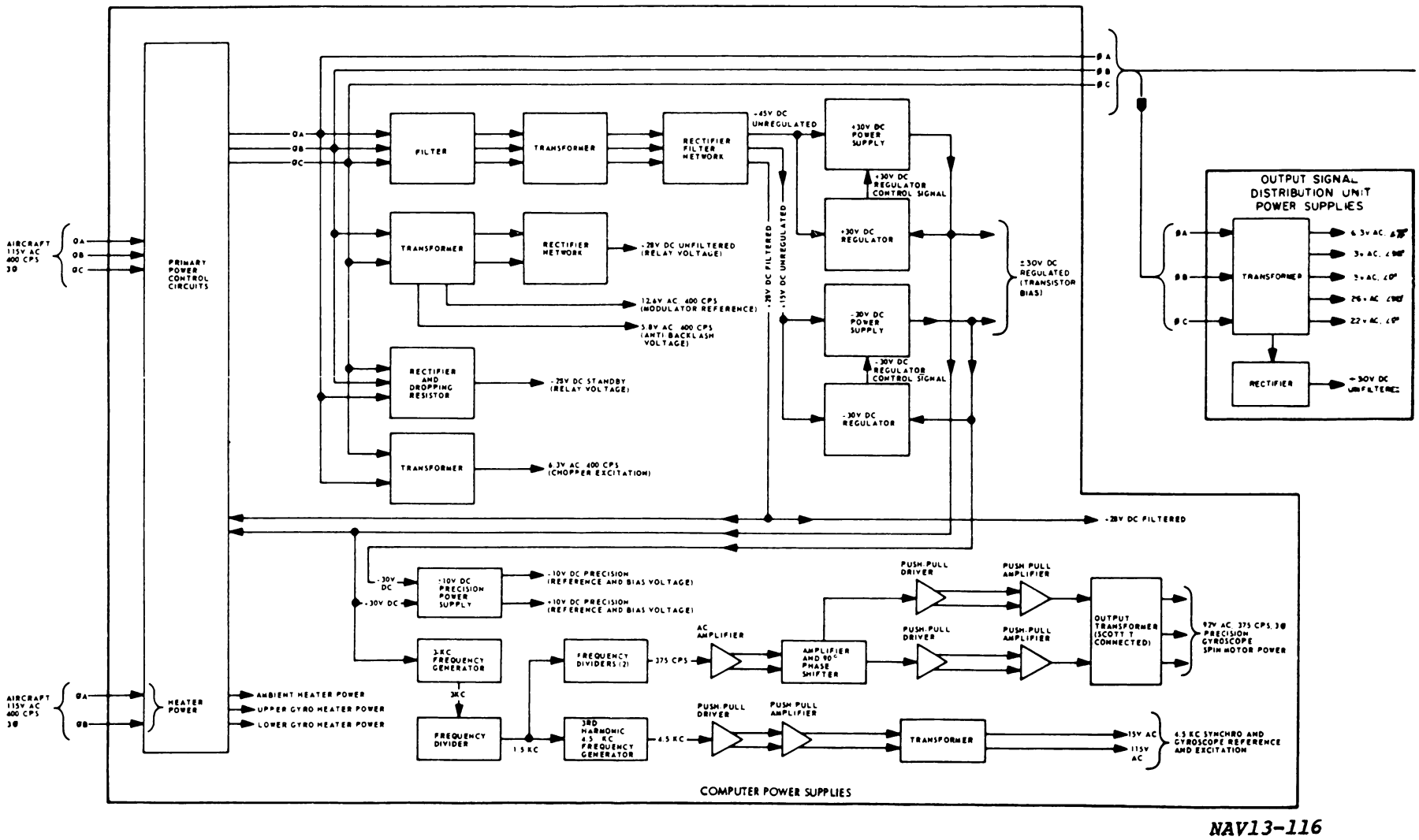

Figure 5–2. Power supply.

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Exercises (624):

Use figure 5-2 to trace the following.

1. What phase of aircraft power is used for ambient heater, gyro heater, and air valve servo power?
2. What are the primary uses of the regulated +30 VDC?
3. What voltage do we use as antibacklash voltage for servos in the INS?
4. What phases of the aircraft power do we use to generate voltage which energizes A3K22?
5. What phases of the aircraft power do we use to generate the excitation voltage for the vibrators?
6. What are the input and output of the second frequency divider located in the computer power supply?
7. What are the sustaining voltages applied to the gyro spin motors in Af, Gc, and NAV?
8. What are the run-up voltages for the gyro spin motors in Ac?
9. What are the outputs of the OSDU power supply?

5-4. Definition of Terms and Symbols

Special equations for acceleration correction, gyro torquing rates, and air navigation are continuously computed throughout the system. In all calculations, the earth is considered to be an oblate spheroid that rotates on a polar axis at a constant angular velocity and moves in inertial space. The symbols and definitions associated with the INS are listed in table 5-2. Study the information in table 5-2 because it will help you to trace signal flow in the system more rapidly.

625. Given system terms and symbols.

INS Equations. The mathematical expressions for the symbols and terms defined in table 5-2 are given in table 5-3. Review the contents of table 5-3 carefully. This information will help you to understand the formation of the signals when they are discussed later in the text.

Note that vertical correction (1.4h Ω) is used in the formula for finding Vx. This vertical correction is applied to the Vx integrator circuit to increase the longitude rate for a given velocity at higher altitudes. Since the INS measures longitude with respect to the center of the earth by forming a curved path above the earth, a given distance traveled at the earth's surface makes a greater change in degrees longitude than the same distance traveled at higher altitudes (fig. 5-3). The higher the altitude, the less the change in degrees for a given distance traveled. For ths reason, the longitude rates increase as a function of altitude, especially near the poles where the lines of longitude converge.

System and Relay Logic Symbols. To simplify the diagrams of the INS, relay logic symbols are used. The symbols are presented in table 5-4. It is very important that you know these symbols well. Otherwise, it will be difficult for you to follow the signal flow throughout the various modes of operation.

Exercises (625):

Identify the following terms as applied to the inertial navigation system represent.

1. Ve.
2. Vg.
3. Vn.
4. λ (lambda).
5. Ω (omega).
6. Coriolis.
7. MAG–HDG.
8. H.

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TABLE 5-2

SYSTEM TERMS AND/OR SYMBOLS

Term or Symbol	*Definition*
A	Acceleration; rate of change of velocity along a predetermined axis.
A_x	Aircraft acceleration along the X-coordinate axis.
A_{xt}	Total acceleration along the X-coordinate axis.
A_y	Aircraft acceleration along the Y-coordinate axis.
A_{yt}	Total acceleration along the Y-coordinate axis.
A_z	Airlift acceleration along the Z-coordinate axis.
A_{zt}	Total acceleration along the Z-coordinate axis.
g	Gravity acceleration (vector sum of mass attraction and earth centripetal force).
H	Inertial altitude.
h_B or $h^\bullet$	Barometric altitude.
R_1	Earth radius (Equator); 2.099×10^7 feet.
R_2	Earth radius (polar); 2.092×10^7 feet.
V	Velocity; rate of linear motion in a predetermined direction.
V_e	Velocity in the east-west direction.
V_g	Aircraft ground velocity.
V_n	Velocity in the north-south direction.
V_x	Velocity along the X-coordinate axis.
V_y	Velocity along the Y-coordinate axis.
V_z	Velocity along the Z-axis.
λ (lambda)	Angle of longitude.
$^\bullet$	Time differential (used as a superscript as in $h^\bullet$).
θ_T	True heading.
ϕ (phi)	Angle of latitude.
Ω (omega)	Rate of rotation of the earth (15.04071°/hr) (earth rate).
ω (omega)	Angular velocity.
ω_x	Angular velocity about the X-axis, or X-axis gyro torquing signal.
ω_y	Angular velocity about the Y-axis, or Y-axis gyro torquing signal.
ω_z	Angular velocity about the Z-axis, or Z-axis gyro torquing signal.
CEP (circular error probability)	The probable navigation error expressed in terms of the radius of a circle centered on the desired terminal point within which 50 percent of the terminal errors will fall.
Geocentric Vertical	An imaginary line perpendicular to the surface straight down toward the earth's center.
Geographic Vertical	Local vertical used in the latitude-longitude coordinate system.
Gravity Vertical	The combined effect of mass attraction and centrifugal acceleration vectors. Coincident with geographic vertical.
Local Vertical	Vertical used in the INS. Coincident with gravity vertical.
Oblate Spheroid	Similar to a sphere but flattened at the poles.
Coriolis	An apparent force at right angles to the direction of motion of an object moving over a rotating reference.
G_c (gyrocompass)	The process by which the system is aligned to true north.
Gyro Precession	Maintaining the stable element or platform level with respect to earth's center.
MAG HDG (Magnetic Heading)	Aircraft heading with reference to magnetic north.
MAG VAR (Magnetic Variation)	The angle between true north and magnetic north.
BATH	Best available true heading (MAG HDG ± MAG VAR).
True Heading	Aircraft heading with reference to true north.
X-axis	X-axis—the platform axis oriented to the east-west direction.
Y-axis	Y-axis—the platform axis oriented to true north.
Z-axis	Z-axis—the platform axis oriented to local vertical.

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TABLE 5-3
SYSTEM CORRECTIONS

Torquing Rates

$$\omega_x = \frac{V_y}{R_2}$$

$$\omega_y = \Omega_y + \frac{V_x}{R_1}$$

$$\omega_z = \Omega_z + \frac{V_x}{R_1} \tan \phi$$

Earth Rates

$$\Omega_y = \Omega \cos \phi$$

$$\Omega_z = \Omega \sin \phi$$

Coarse Align (A_c)

Synchro (pitch and roll gimbals) + A-C BATH (azimuth gimbal) (Synchro)

Fine Align (A_f)

ω_x = Bias (X-gyro) + A_y (north accelerometer sensing gravity)

ω_y = Bias (Y-gyro) + A_x (east accelerometer sensing gravity) + $\Omega \cos \phi$ (earth rate)

ω_y = Bias (Y gyro) + A_x (east accelerometer sensing gravity) + $\Omega \cos \phi$ (earth rate)

ω_z = Bias (Z gyro) + D-C BATH (torquing) + $\Omega \sin \phi$ (earth rate)

Gyrocompass (G_c)

ω_z = Bias (Z gyro) + A_y SECANT ϕ (INS true north) + $\Omega \sin \phi$ (earth rate)

Navigate (NAV)

ω_x = Bias (accel) + $\frac{V_y}{R_2}$ (craft rate)

ω_y = Bias (accel) + $\frac{V_x}{R_1}$ (craft rate) + $\Omega \cos \phi$ (earth rate)

ω_z = Bias (accel) + $\frac{V_x}{R_1} \tan \phi$ (craft rate) + $\Omega \sin \phi$ (earth rate)

V_x = Bias (accel) + $\frac{V_x V_y}{R_1} \tan \phi$ (centripetal) + $2\Omega V_y \sin \phi$ (coriolis) + $A_x - 1.4\ h \cdot \Omega$ (vertical correction)

V_y = Bias (accel) + $\frac{V_x^2}{R_1} \tan \phi$ (centripetal) + $2\Omega V_x \sin \phi$ (coriolis) + A_y

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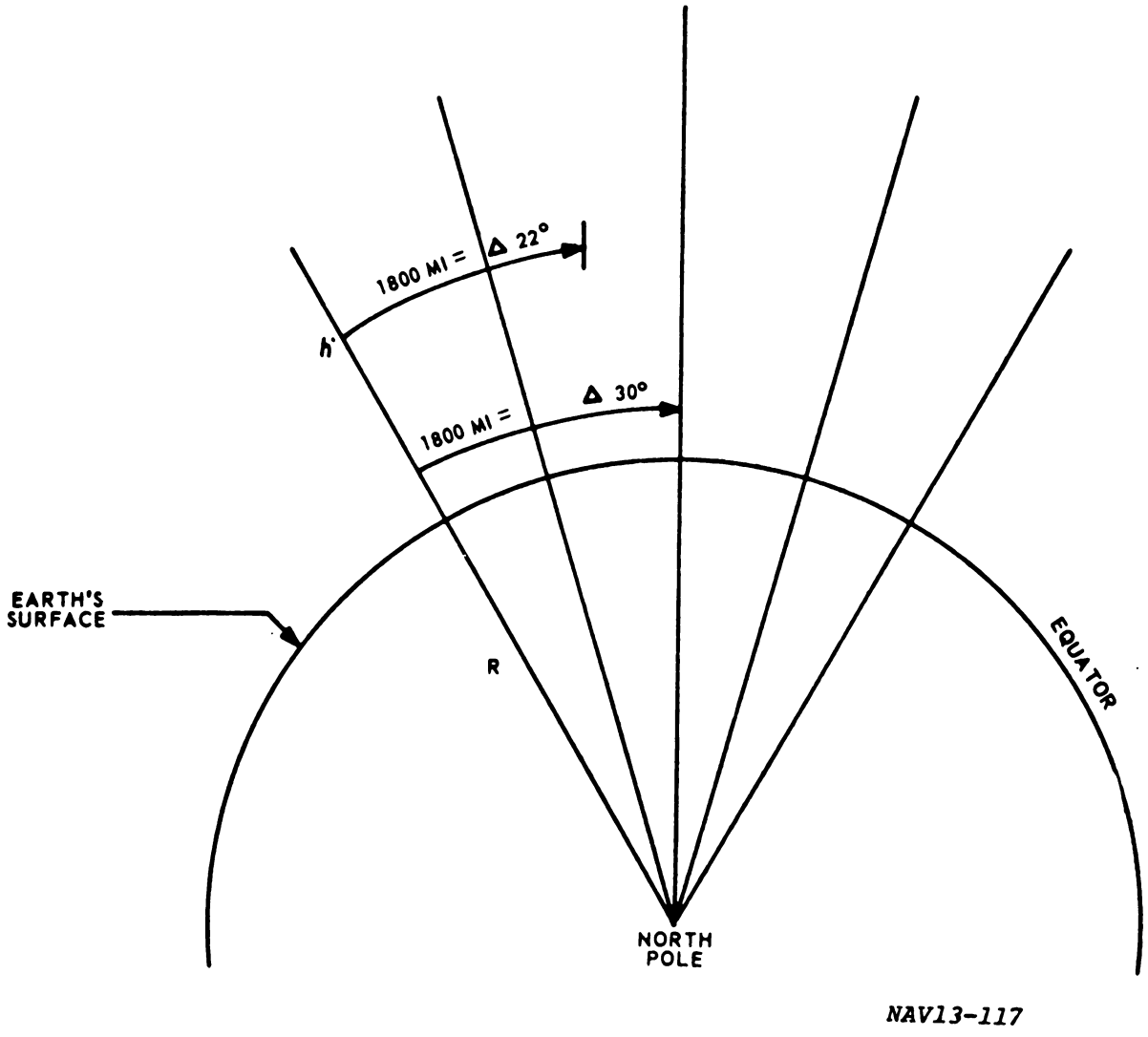

Figure 5–3. Vertical correction.

5-5. Modes of Operation.

The INS is operational in three of its four modes: standby, align, and navigate. The fourth mode is the off mode. No power is applied to the INS in this mode. In the standby mode, power is applied to the platform and computer environmental controls. During the align mode, the stable element is leveled with respect to local vertical and aligned to true north. The INS is fully operational in the navigate mode. You select the mode of operation by setting the control unit mode selector switch to any of the positions: OFF, STBY, ALIGN, or NAV. Now, let us see what happens in each mode.

626. State the purpose of each mode or phase of operation of the INS.

Standby Mode. You set the control unit mode selector switch to STBY to prepare the INS for operation. The INS has two modes of operation with the mode selector switch set to STBY. The two standby modes are determined, external to the INS, by the external navigation computer. When the external computer is on, aircraft 28 VDC is applied to the computer power supply 3A25, the environmental circuits are energized, and course align is initiated. When the external computer is off, aircraft 28 VDC is not applied to computer power supply 3A25, and only the INS environmental circuits are energized. With the environmental circuits energized, the platform gyros and accelerometers and computers oven assembly 3A22 are heated to operating temperature.

Align Mode. The align mode takes place in three consecutive phases: coarse align (Ac), fine align (Af), and gyrocompass (Gc). In these three submodes, the stable element of the INS is leveled with respect to local vertical and oriented to true north. Alignment begins

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Table 5-4

SYSTEM RELAY LOGIC

NOTE: Time notation of relay logic symbols indicate relay is energized during one mode and another mode, i.e., $75A_FM$ indicates relay is energized 75 seconds after fine align during heading memory. Relays are energized during the modes indicated adjacent to the relay and are deenergized during all other modes.

A	Energized when mode selector is set to either STBY or ALIGN (S+A).
$\overline{SA}$	Energized only when mode selector switch is set to ALIGN.
S_1	Energized only when mode selector switch is set to STBY.
60A	Energized 60 seconds after mode selector switch is set to either STBY or ALIGN from OFF.
$\overline{60A}$	Energized for first 60 seconds after mode selector switch is set to either STBY or ALIGN from OFF.
A_F	Energized when mode selector is set to ALIGN, if INS was previously in STBY mode for more than 60 seconds, or energized 60 seconds after mode selector switch is set to ALIGN from OFF.
A_C	Energized when mode selector switch is set to STBY or for 60 seconds after it is set to ALIGN from OFF.
0.25A	Energized 250 milliseconds after mode selector switch is set to either STBY or ALIGN.
G	Energized 110 seconds after gyros are at predetermined operating temperature; 75-second time delay has been accomplished and GYRO COMP/HDG MEM switch is set to GYRO COMP.
$\overline{G}$	Not energized during gyrocompass.
$\overline{T}$	Energized when gyros are not at predetermined operating temperature.
T	Energized when gyros are at predetermined operating temperature.
60T	Energized 60 seconds after gyros are at predetermined operating temperature.
110T	Energized 110 seconds after gyros are at predetermined operating temperature.
$\overline{F}$	Energized when no fault is detected in the attitude computer.
F_P	Energized when the position fix signal is present from the navigational computer set.
$\overline{F}_P$	Not energized when position fix signal is present from the navigational computer set.
H	Energized during coarse align hold testing.
$\overline{H}$	Not energized during coarse align hold testing.
L	Energized when level detector indicates azimuth alignment completed.
50LG	Energized 50 seconds after gyrocompass initiate and level detector indicates azimuth alignment completed.
M	Heading memory (energized when GYRO COMP/HDG MEM switch is set to HDG MEM).
$\overline{M}$	Not energized during heading memory alignment.
N	Navigate (energized during entire time mode selector is set to NAV).
0.25N	Energized after 250 milliseconds during navigate mode.
4N	Energized after first 4 seconds during navigate mode.
$\overline{P}$	Not energized for 500 milliseconds after a power interrupt of greater than 1 millisecond, but less than 50 milliseconds.
S_D	Energized during Schuler loop disable testing.
UP	Energized when landing gear control switch is in the UP position.
$V_Z{}^h{}_B$	Energized during barometric altitude, vertical velocity stabilization.
+	Energized during one mode or another, i.e., A+N indicates relay is energized during ALIGN or NAV.
ϕ>70°	Energized when north or south latitude is greater than 70°.
-ϕ	Energized when in south latitudes.

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when you set the control unit HDG MEM/GYRO COMP switch to GYRO COMP. Stable element alignment accuracy during Ac and Af depends on the accuracy of the magnetic compass and the platform temperature.

Coarse align submode (Ac). In Ac, the stable element is oriented from a random position to an approximate true north and coarse level position, and the gyros are allowed to attain normal operating rotational speed. The coarse align phase may be initiated when the selector switch is set to STBY or ALIGN. The platform level-axis synchro transmitter outputs provide signals that drive the corresponding platform level-axis gimbal servomotors, caging the inner roll, outer roll, and pitch gimbals to an approximate aircraft attitude position. The OSDU true heading servoloop supplies an azimuth slaving signal that orients the stable element to approximately true north (BATH). BATH is the *best available true heading* signal and is a combination of magnetic heading and magnetic variation. BATH information, derived from a navigational computer system, positions the followup servoloop in the OSDU.

Stable element heading, in the form of a synchro transmitter signal, is applied to a synchro control transformer in the OSDU (see upper right, foldout 1). The control transformer is geared to the true-heading followup shaft. The electrical information on the rotor windings of the synchro control transformer represents the error signal between BATH and the azimuth orientation of the stable element. This error signal drives the platform azimuth servomotors that position the stable element to BATH. The Ac phase is completed within a few seconds after the start of alignment. However, the INS remains in the Ac phase until the gyros reach operating rotational speed.

Fine align submode (Af). When you switch to ALIGN, the Af phase is started. In Af, the accelerometers sense any sense any deviation from level and produce error signals. The accelerometer error signals are applied to appropriate gyro axes to torque the platform to a level condition. The Af phase is completed in approximately 75 seconds. However, the INS remains in the Af phase until the heat indicator has been out for 50 seconds.

Gyrocompass submode (Gc). The phase of alignment is automatically initiated 75±15 seconds after the start of align, if the heat indicator has been extinguished for 50 seconds. At the beginning of the Gc alignment, the control unit align indicator lights up to show that Gc alignment has started.

The main function of Gc is to provide the final azimuth alignment of the platform. If an error exists in the alignment of the Y-axis to true north, the actual earth rate component along the X-axis for the specific orientation causes the stable element to precess about the X-axis. The precession causes the stable element to be driven away from the level position. When the stable element deviates from the level position, the Y-axis accelerometer produces a signal—Ay. The Ay is used to compute the torquing signal that must be applied to the Z-axis gyro-torquing coils. The stable element is torqued until the azimuth axis is positioned to true north. At the completion of Gc alignment, the control unit align indicator flashes. This indicates that the Gc alignment is completed and the system will now provide navigational accuracies of better than 3 NM per hour flight.

Navigate (NAV). When you set the mode selector switch to NAV, the INS is fully operational. The INS continuously solves the navigation problem. The basic functions performed by the computer are integration of horizontal accelerations into velocity and integration of velocity into distance. The operation of the computer is based upon a latitude/longitude coordinate system that uses a geographic vertical reference and an azimuth orientation. Computations require DC signals, while AC signals are used for driving motors, stabilizing DC amplifiers, and transmitting latitude and longitude signals, north-south velocity (Vn), and east-west velocity (Ve) outputs. Capacitance tachometers, integrator shafts, integrating DC amplifiers, summing amplifiers, and their associated circuits provide continuous solution of the navigation problem and orientation of the stable element regardless of aircraft attitude.

Exercises (626):

1. State the purpose of the standby mode.

2. State the purpose of the coarse align submode.

3. State the purpose of the fine align submode.

4. State the purpose of the gyrocompass submode.

5. State the purpose of the navigate mode.

627. Differentiate between the two types of rapid alignment.

Rapid Alignment. If required, rapid alignment may be used to reduce the time of INS alignment. However, reduction of alignment time reduces the accuracy of the system. Two choices of rapid alignment are available—heading memory alignment or BATH alignment. Heading memory alignment can be accomplished if the system has been aligned previously and the true heading of the stable element has been stored before the system was turned off. They are similar in alignment time and navigational accuracy. (Better than 5 NM per hour are possible at temperatures above −20° F. To attain this accuracy at lower temperatures requires a longer

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warmup time.) Both rapid alignments have a distinct disadvantage. In heading memory, once the INS has been turned off, the aircraft cannot be moved. BATH employs a combination of magnetic heading and magnetic variation and, therefore, cannot be used while the aircraft is inside or near a hangar or any large metal object that disturbs the earth's magnetic lines of force.

Heading memory. Heading memory alignment can be used only when the aircraft is allowed to remain stationary after the system has been turned off. In this alignment procedure, you let the system gyrocompass normally. At the completion of gyrocompassing, you set the HDG MEM/GYRO COMP switch to HDG MEM, locking the true heading followup shaft in the OSDU. You then turn the system off. To use HDG/MEM you must turn on the external navigation computer before setting the selector switch to STDY. Then, when the INS is turned on again, the stable element is torqued rapidly until the output of a synchro control transformer, driven by the true heading followup shaft, is nulled. When the output of the control transformer is nulled, the heading of the stable element coincides with the fixed position of the heading followup shaft. At the completion of heading alignment, the control unit ALIGN indicator flashes.

BATH. In a BATH alignment, magnetic heading and variation are combined to position the stable element. In this alignment procedure, you allow the system to align normally. When the system enters Gc, the NAV mode is immediately selected. The stable element true heading is now positioned to BATH.

Exercises (627):

Identify the alignment being described as *heading memory* or *BATH*.

1. In which kind of alignment can the aircraft not be moved after the INS has been turned off? In which kind of alignment can the INS not be used near any metal object that will affect magnetic lines of force?

2. In which kind of alignment is a shaft in the OSDU locked-up? in which kind of alignment is a signal from the associated computer used to align the INS?

5-6. System Alignment Sequencing

The following discussion of system alignment emphasizes the sequencing of time delay circuits that must be energized before alignment can continue. In explaining the system alignment sequencing, we use figure 5-4. Study each component or circuit on figure 5-4 as it is discussed in the text.

628. Identify the purpose of given time delay relays.

System alignment begins when S1 (bottom of fig. 5-4) is positioned to STBY. When the upper and lower gyro heat is within tolerance, the heat detector circuit (in 3A23) removes ground from the heat indicator light, causing it to go out. In addition, the heat detector starts the 50-second time delay (TD) in 3A8. This allows the gyro temperature time to stabilize. After 50 seconds, it provides ground to gyrocompass initiate relay K11. (K11 does not energize at this time.)

In the align mode, S1B provides 28 VDC to initiate the 60-second TD in 3A8. This TD establishes the duration of Ac by delaying the start of Af for 60 seconds after S1B is switched to the standby or align position. After 60 seconds, the TD provides ground for Af initiate relay K27, a self-holding relay that is energized in Af, Gc, and NAV. When energized, K27 provides 28 VDC to start the 75-second TD on assembly 3A14. This TD relay establishes the duration of Af by delaying the start of GC for 75 seconds after the completion of Ac. The −30-VDC output of the 75-second TD energizes gyrocompass "initiate relay" K11 and lights the align light. The gyrocompass signal, a DC voltage analog of Ay sec ϕ, is applied to the level detector on the 3A14 assembly. When the DC voltage analog of Ay sec $ phi $ is between +10 VDC and −10 VDC, the level detector provides ground for K29. This ground causes K29 to energize and provide +28 VDC to the level detector 50-second time delay to insure that Ay sec ϕ remains within limitation for 50 seconds, insuring reliability of the signal. After 50 seconds in the level condition, the level TD provides ground to energize ready relay K21. Energized, K21 provides 28 VDC to K30 and the flasher circuit, which energizes and deenergizes flasher relay K30 at a 1-Hz rate. The align light goes on and off at the same rate, indicating alignment is completed. The mode selector switch can now be placed in the NAV position.

Exercises (628):

Match the purpose in column A with the TD relay from column B.

Column A	*Column B*
____ 1. Allows the gyro temperature time to stabilize.	a. 75-second TD.
____ 2. Establishes duration of Ac.	b. 50-second TD.
____ 3. Establishes duration of Af.	c. 60-second TD.
____ 4. Lights the align light.	d. Level 50-second TD.
____ 5. Insures reliability of Ay sec ϕ.	

In this section, we explain the sequence of operation from standby mode through navigate mode. For this discussion, refer to foldout 1 to find components and trace the signal through loops being discussed.

629. Cite operational characteristics of environmental circuits.

Standby. Although coarse align can be started in standby mode, the standby mode is primarily a heating

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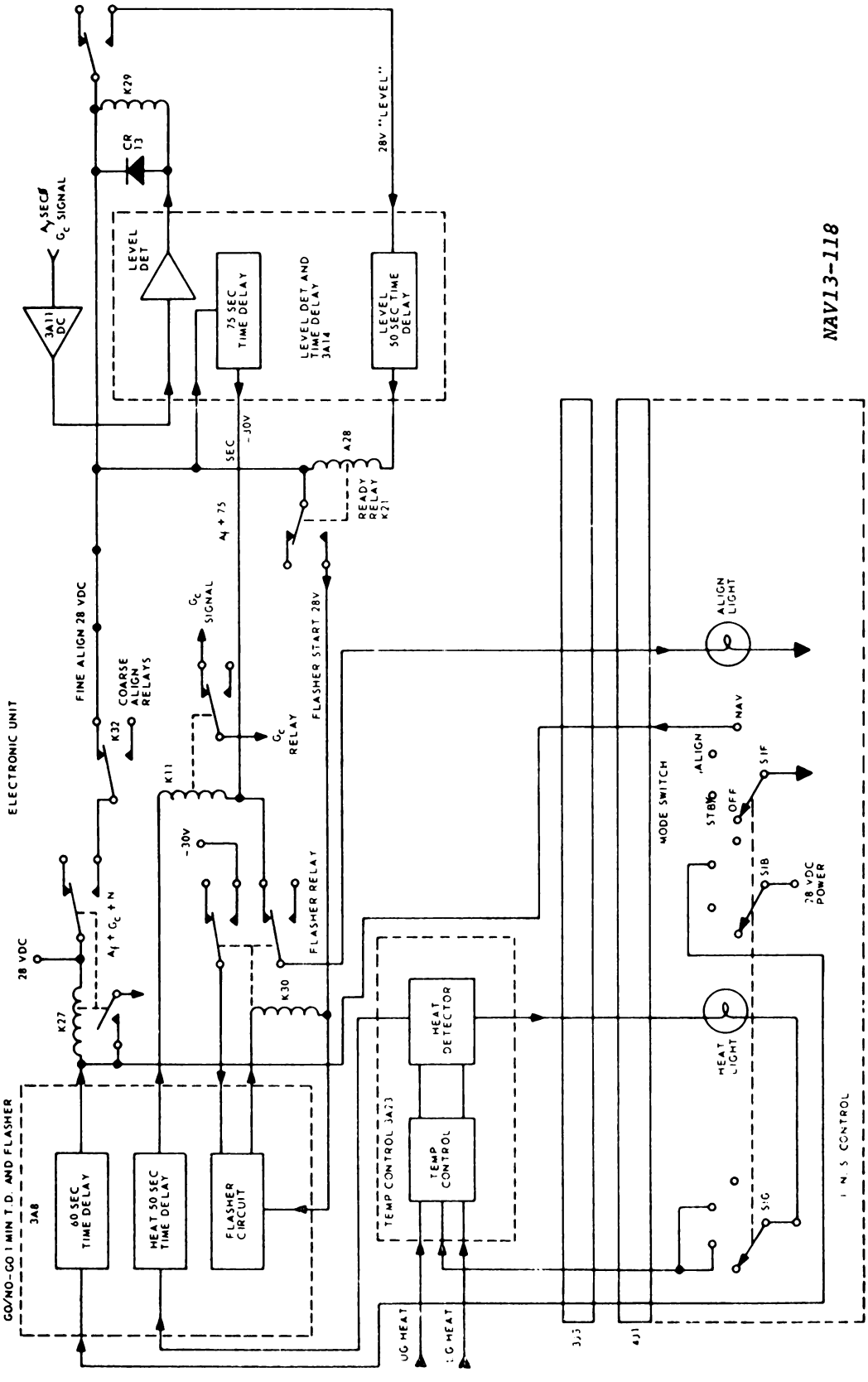

Figure 5-4. Delay circuits.

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mode, with environmental circuits energized to bring the platform gyros and accelerometers to operating temperatures (fig. 5-4). The temperature control assembly 3A23 is located on the navigator computer, and the heaters and thermistors on the stabilized platform. Note that the temperature control circuits are energized by the mode selector switch through power supply assembly 3A25. The temperature control assembly provides voltage to the heaters. Once the heater reaches the proper temperature, the thermistors send the temperature control circuits the signals necessary to control the heater voltage. When thermistors are in the circuit, the control circuits remove ground from the heat indicator on the INS control. This causes the indicator to go out, showing that the right temperature has been reached.

Exercises (629):

1. Which assembly provides voltage to the heaters?

2. Once proper temperature is attained by the heater, what provides the temperature control circuits with the signals necessary for control of the heater voltage?

3. What does a glowing HEAT indicator on the control unit simplify?

630. State characteristics of signals used to cage the gimbals of the stable element to the aircraft attitude during coarse align phase.

Coarse Align (Ac). Refer to foldout 1. In Ac the platform level-axis synchro transmitter outputs provide signals that drive the corresponding platform level-axis gimbal servomotors caging the inner roll, outer roll, and pitch gimbals to an approximate aircraft attitude position. The OSDU true heading servoloop supplies the azimuth slaving signal to orient the stable element to approximately true north. True north information is provided by an associated navigational computer. Now, we will discuss the leveling loops used during Ac to level the platform.

Outer roll servoloop. During Ac, 115–VAC 4.5-kHz excitation is applied to outer roll gimbal control transmitters BCX4 and BCX6. See the upper right corner of the platform in foldout one. The output of BCX4 is applied to both outer roll servoamplifiers 3A1, which are located in the platform electronics section of the navigator computer. The outputs of the 3A1 amplifiers drive outer roll gimbal servomotors BM7 and BM8 until the output of outer roll control transmitter BCX4 is nulled. At this time, the outer roll gimbal is aligned approximately to the attitude of the aircraft.

Pitch servoloop. In Ac, 115-VAC 4.5-kHz excitation is applied to pitch control transmitters BCX3 and BCX5. The output of BCX3 is applied to pitch servoamplifier A3A. The output of the amplifier drives pitch gimbal servomotors BM5 and BM6 until BCX3 is nulled. At this time, the pitch gimbal is aligned with the aircraft (horizontally).

Inner roll servoloop. During Ac, 115-VAC 4.5-kHz excitation is applied to inner roll control transmitter BCX2. The output of BCX2 is applied to inner roll servoamplifier 3A3. The output of 3A3 (inner roll servoamplifier) drives inner roll gimbal servomotors BM3 and BM4 until BCX2 is nulled.

Azimuth servoloop. The azimuth servoloop operates somewhat differently from the other loops in that it is controlled by BATH signals supplied by the navigational computer. The BATH signal positions the true-heading servoshaft in the OSDU to true north. In Ac, when the angular position of the stable element and angular position of the true-heading servoshaft in the OSDU do not coincide, a 4.5-kHz azimuth signal is produced at control transmitter BCX 1 in the platform and sensed by the rotor of OSDU control transformer B2. The presence of a 4.5-kHz error signal indicates an error between true north and the azimuth orientation of the stable element. This error signal is amplified, modulated at 4.5 kHz, and demodulated in true-heading servoassembly 2A1. From 2A1, the signal is applied to azimuth servoamplifier 3A2 in the computer. The output of 3A2 is applied, as an azimuth gimbal drive signal, to azimuth gimbal motors BM1 and BM2. BM1 and BM2 drive the stable element (azimuth gimbal) until the output of OSDU control transformer B2 is zero, indicating that the angular position of the stable element and the OSDU true heading servoshaft are in coincidence.

Exercises (630):

1. What is the approximate alignment of the outer roll gimbal in Ac when BCX4 has no output?

2. Refer to foldout 1. Which assembly provides the drive voltage of BM5 and BM6 in Ac?

3. What is the amplitude and frequency of the excitation voltage applied to the inner roll control transmitter during Ac?

4. What is the output of the inner roll servoamplifier, 3A3, in Ac when BCX2 has no output?

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5. What is the frequency of the signal produced during Ac when the angular position of the stable element and the true heading servoshaft in the OSDU are not in coincidence?

6. When the angular position of the stable element and the OSDU true heading servoshaft are in coincidence, what is the output of BM1 and B1?

631. Using a block diagram, state the purpose or function of selected signals in the accelerometer restoring loops and gyro torquing loops used in the fine align (Af) phase.

Fine Align (Af). Af is an automatic submode of the align function. The gyros reach operating rotational speed before the INS goes into the fine align phase. In Af, the accelerometers are used to sense gravity and to control the gyros. The gyros, in turn, control the fine leveling of the platform. Deviation of the stable element from level is sensed by the X- and Y-accelerometers (fig. 5-5). The resulting error signals are applied to the X- and Y-torquing coils of the upper and lower gyros. The gyro pickoff signals are amplified and applied to a servomotor that drives the gimbals and cancels the accelerometer pickoff error signals. Angular deviation of the stable element from the gyro reference produces gyro pickoff signals. These pickoff signals are resolved, amplified, and applied to the torquing motor, and drive the gimbals until the pickoff error signals are cancelled. Thus, the stable element is slaved to the gyros and maintains proper orientation. (Refer now to fig. 5-5 and study this paragraph again.) A series of loops, similar to those used during Ac, maintains the stable-element level and properly oriented. In Af, we use accelerometer restoring and gyro-torquing loops. Let us see how these loops work.

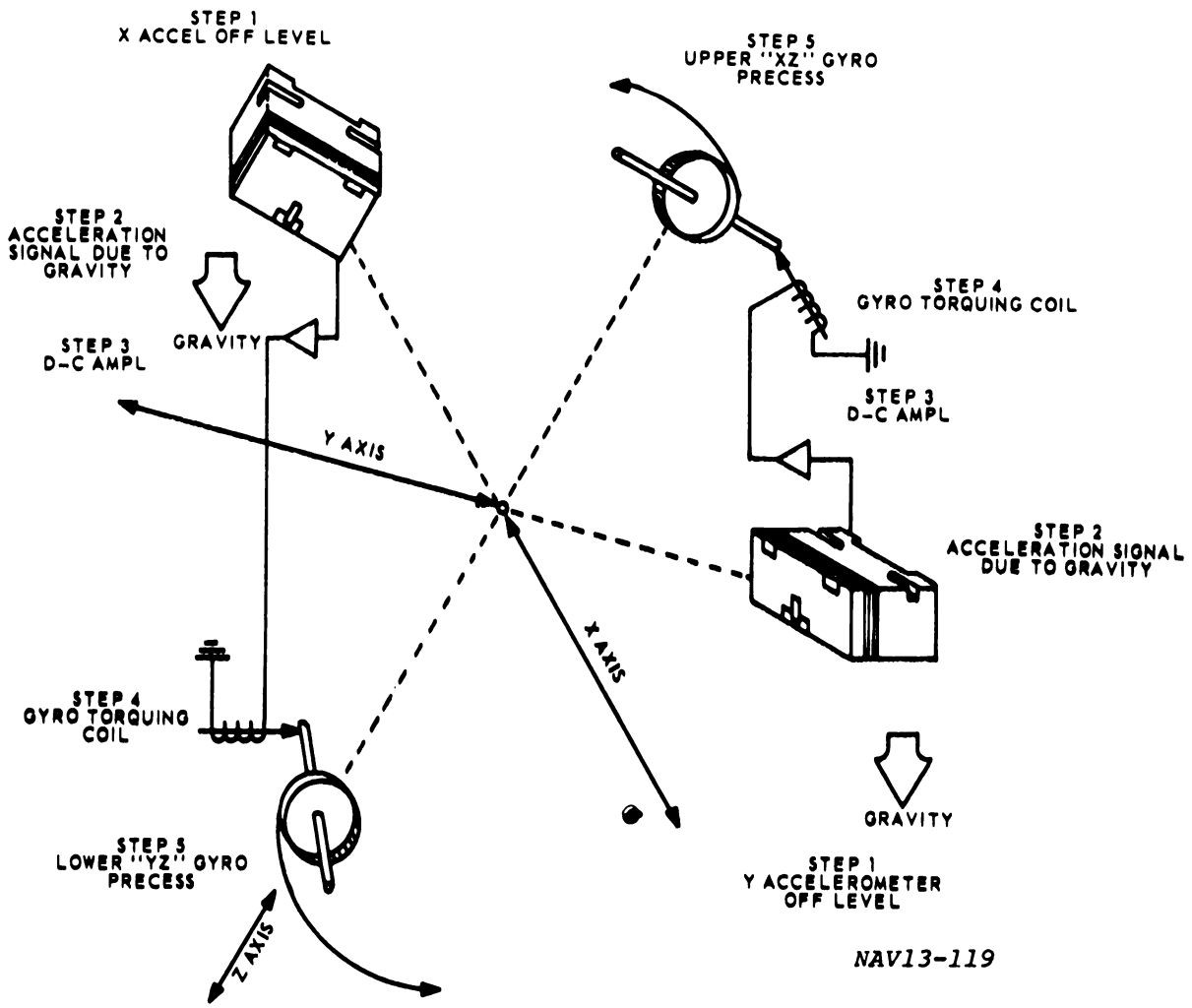

Figure 5-5. Accelerometer sensing gravity.

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Accelerometer restoring loops. Three separate accelerometer restoring loops reposition the three floated pendulous elements of the X-, Y-, and Z-accelerometers. The accelerometers must be repositioned whenever a displacement of the element occurs as a result of an acceleration. Since the three accelerometer restoring loops are identical, we discuss only the X-axis accelerometer restoring loop.

When the sensitive element of the X-accelerometer is displaced, the accelerometer generates a 4.5-kHz error signal (FO 1 and fig. 5-6). This error signal is applied to accelerometer restoring amplifier assembly 3A7 of the platform electronics section of the computer, where it is amplified and mixed with a 15-VAC 4.5-kHz/180°X reference signal. The signal out of the mixer is demodulated. The output of the demodulator is a DC whose polarity depends on the phase difference between the 4.5-kHz reference signal and the accelerometer error signal. After further amplification, the DC signal is applied to the X-accelerometer torquer coil. It drives the floated pendulous element until the X-accelerometer 4.5-kHz pickoff error signal is zero.

Y-gyro torquing loop. In explaining the gyro-torquing loops, we assume that the aircraft is pointing exactly to true north. Therefore, any misalignment of the stable element along the X-axis is sensed by the X-accelerometer (FO 1 and fig. 5-7). The resulting error signal (Ax) is applied to DC amplifier assembly 3A4. From 3A4, the amplified Ax signal is applied through summing amplifier assembly 3A17 to the Y-torquer coil of the lower gyro, YZ1. The signal causes gyro YZ1 to precess. Precession of the gyro YZ1 causes the pickoff coil to generate a signal. The Y-gyro pickoff signal is applied through the azimuth resolver, inner roll servoamplifier assembly 3A3, the integrator shaft assembly 3A24 to the inner roll servomotors that drive the inner roll gimbal. (Note that the 3A24 assembly is *not* shown on foldout 1.) However, in each case in this system, drive signals from servoamplifiers must be routed through power amplifiers and then to the servos. The power amplifiers provide the necessary voltage and frequency needed to drive the servos. The inner roll servomotor drives the gimbal until the sensed output of the X-accelerometer is nulled. During Af, the outer roll gimbal is caged to the inner roll gimbal. This caging is done by BCX2 on the inner roll gimbal (foldout 1). The output of BCX2, after it is amplified in outer roll servoamplifier 3A1, drives the outer roll servomotor until the outer roll gimbal and the inner roll gimbal are aligned and BCX2 is nulled.

X-gyro torquing loop. Any misalignment of the stable element along the X-axis is sensed by the Y-accelerometer (FO 1 and fig. 5-7). The resulting error signal is applied through DC amplifier assembly 3A10 to the X-torquer coil of upper gyro XZ2. This signal causes XZ2 to precess. The precession causes the gyro pickoff coil to generate a signal (X-gyro signal), which is applied through the azimuth resolver, pitch servoamplifier 3A3, and integrator shaft assembly 3A24 to the pitch gimbal drive motors. The motors drive the gimbal until the output of the Y-accelerometer is nulled.

Z-gyro torquing loop. Misalignment between the true-heading shaft in the OSDU and the BATH signal from the navigational computer provides the demodulator in assembly 2A1 with an error signal (FO 1 and fig. 5-7). The output of the demodulator is applied through 3A17 and 3A18 to the Z1-axis torquer of the YZ1 gyro. The output of 3A18, ω z, causes the gyro to

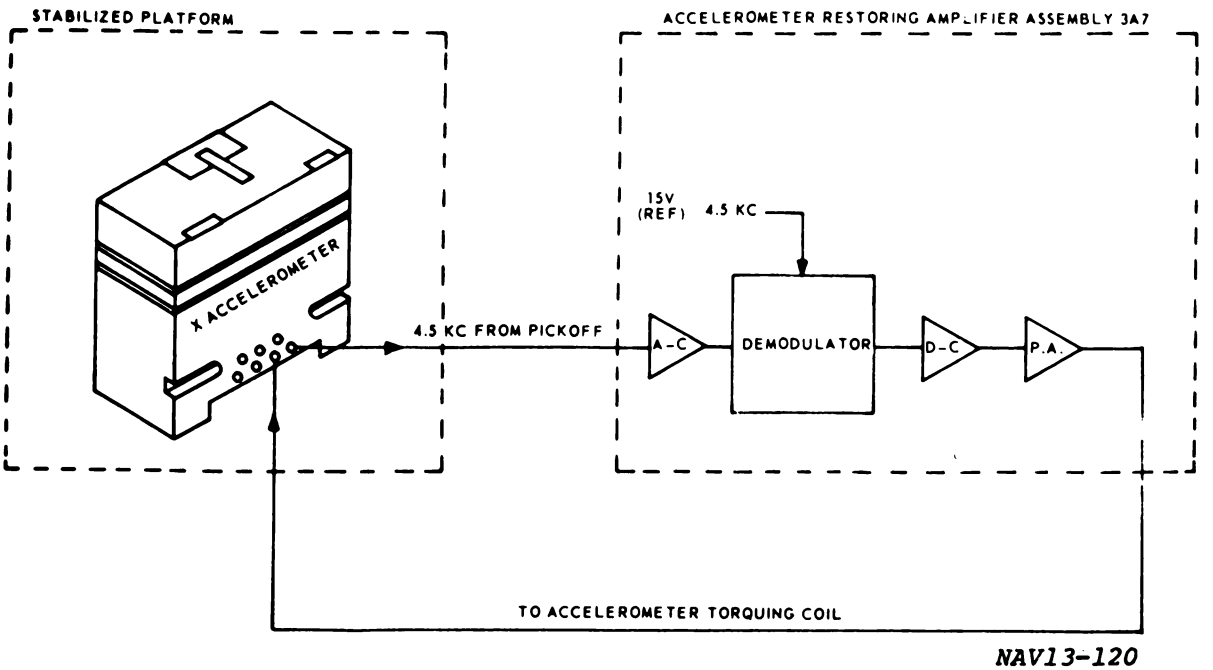

Figure 5–6. Accelerometer restoring amplifier.

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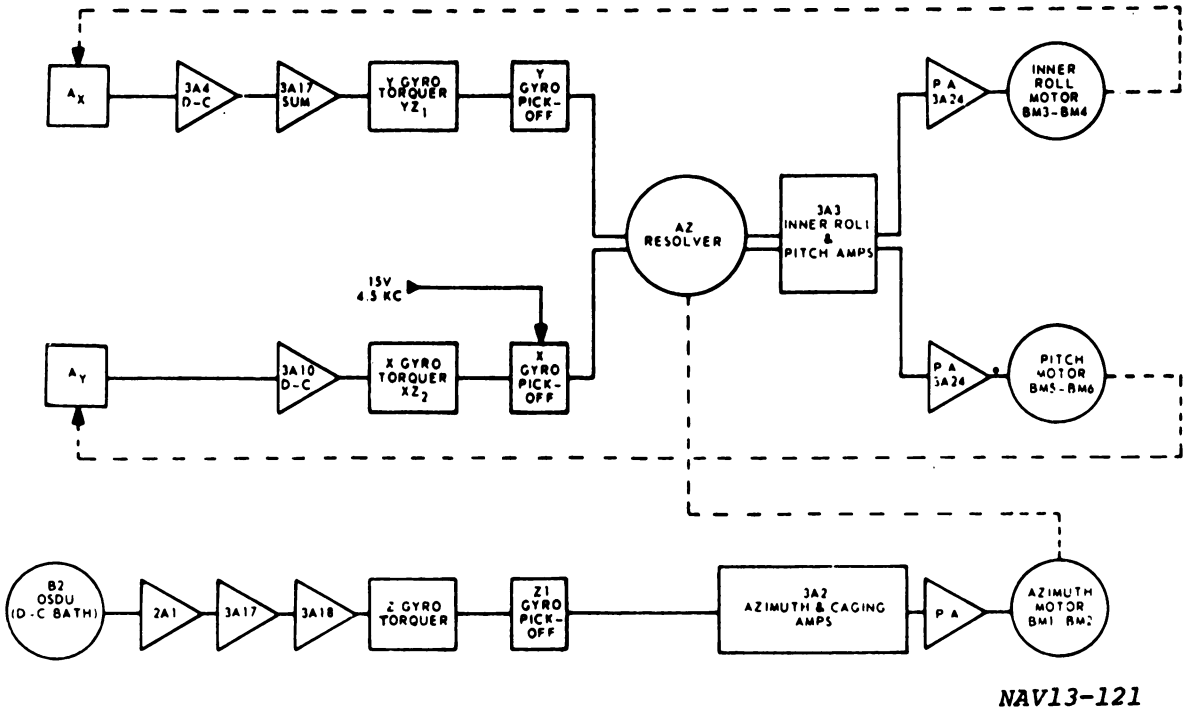

Figure 5–7. Torquing loops.

precess. The precession causes the Z1-axis pickoff to generate a signal which is amplified in azimuth servoamplifier 3A2 and applied to the azimuth servomotors. The motors drive the azimuth gimbal until the stable element is aligned to the BATH signal. The Z2-axis is caged to the Z1-axis. This is done by applying the output of the Z2- and Z1-pickoff coils to azimuth servo and caging amplifier assembly 3A2 (foldout 1). The output of 3A2 is applied to the upper gyro XZ2 torquer. The amount of torque is such that it aligns the Z2-axis with the Z1-axis.

Exercises (631):

1. Refer to foldout 1. In Af, what controls the leveling of the platform?

2. In Af, how is proper orientation maintained?

3. What determines the output polarity of X-accelerometer restoring amplifier 3A7?

4. Refer to foldout 1. During Af, with the aircraft pointing due north, where are the accelerometer signals applied?

5. What is the function of BCX2 output during Af?

6. Refer to foldout 1. During Af, what causes the pitch gimbal drive motor (BM5–BM6) to drive?

7. Refer to foldout 1. During Af, what is the output of assembly 3A18, and where is it applied?

8. Describe the torque applied to the XZ2 torquer in Af.

632. Using an INS block diagram, cite the two components that develop AY sec ϕ for azimuth alignment in the gyrocompass phase.

Gyrocompass. Gyrocompass is an automatically initiated submode that starts 75 ± 15 seconds after

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selecting the align mode. In gyroscompass, the leveling signals applied to the X- and Y-axes of the gyros are the same as those used during fine align. The primary differences between fine align and gyrocompass are in the azimuth alignment and Z-gyro torquing loops.

For the final azimuth alignment in the gyrocompass phase of the align mode, we use the output of the Y-accelerometer, Ay (FO 1 and fig. 5-8). The Ay signal is applied through assembly 3A10 to secant potentiometer R18C, located on latitude integrator and shaft assembly 3A24. The output of R18C (+ Ay sec ϕ) is applied to summing amplifier 3A18. The output of 3A18 (ωz) is applied to the Z1-axis torquer coil. This causes the Z1-pickoff coil to produce an output. The output from the pickoff coil is applied through azimuth servo-amplifier assembly 3A2 to azimuth servomotors BM1 and BM2. BM1 and BM2 drive the stable element until the Z1-pickoff signal is nulled. When the output of the Y-accelerometer reaches zero and remains at zero, the Ay sec ϕ has given the system its final azimuth alignment and the gyrocompass phase of alignment is completed. We now have the stable element level in respect to local vertical and the azimuth aligned to true north. We have our frame of reference established with all three axes aligned properly.

Exercises (632):

1. During gyrocompass phase, what element senses misalignment of the stable element about the azimuth axis?

2. The signal from the component in question 1 is run through what component to convert it to a secant of latitude?

3. Refer to foldout 1. Where is the output of the 3A17 amplifier applied?

4. What is the output of the Y-accelerometer when gyrocompass is completed?

633. Using an INS block diagram, trace the signals developed in the navigate mode.

Navigate. In the navigate mode, the primary function of the leveling and azimuth loop is to maintain the frame of reference that was established in the align mode. To prevent the accelerometers from sensing anything but true tangential velocities of the vehicle, it is imperative that the frame of reference be maintained. The true tangential velocity of the vehicle is the basis for the corrections used in the navigate mode. Accelerometer outputs in the navigate mode are integrated with time to develop velocities. These velocities are used to drive the displacement integrators and to develop gyro-torquing signals corrected for craft rate. The accelerometer outputs are integrated by integrator shaft assembly 3A24 (FO 2). The 3A24 assembly has four integrator shafts (which provide the computed velocity and distance traveled outputs), the power output transistors for the gimbal servoamplifier outputs, demodulators for longitude and latitude inputs, and a synchronizer for the dual latitude synchro inputs. You can see the circuits discussed in the rest of this lesson in foldout 2.

Vx integrator circuit. The X-velocity integrator provides ± Vx signals corresponding to aircraft velocity along the X-axis (upper left of FO 2). The Vx integrator circuit comprises DC amplifier 3A4, two power amplifiers 3A9, Vx integrator shaft assembly 3A24, DC amplifier 3A5, and two summing amplifiers 3A6. The X-accelerometer signal, bias, vertical correction, and centripetal and coriolis accelerations are applied to DC amplifier 3A4. The sum of these input signals is amplified in 3A9 and applied as the drive signal to the Vx integrator motor. The output of the Vx integrator shaft, −Vx, is corrected for the equatorial radius of the

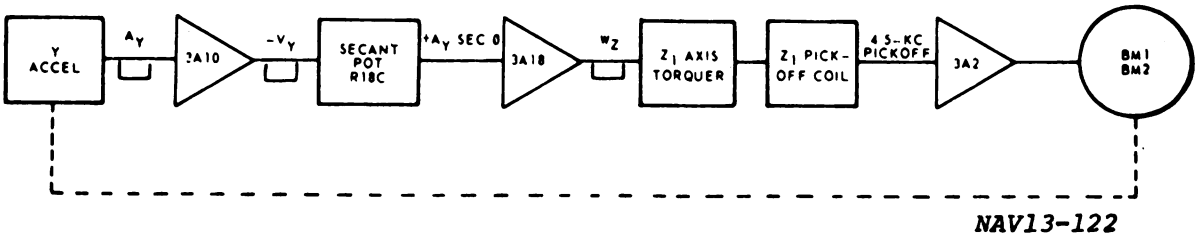

Figure 5-8. Azimuth torquing loop.

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earth by resistive network R1 at the input to assembly 3A6. In the Vx integrator circuit, the output of 3A6, $\frac{-Vx}{R1}$ serves two purposes: It is applied to assembly 3A17 as transport, and it is amplified in assemblies 3A5 and and 3A9 and applied to the longitude integrator shaft. (The outputs to the latitude to the longitude integrator shaft. (The outputs to the latitude integrator shaft will be discussed later.) The longitude integrates $\frac{-Vx}{R1}$ proportional to the secant of latitude because of the converging longitude lines at high latitudes. The Vx integrator shaft also provides Ve and Vw to a navigational computer.

Longitude integrator circuit. The inputs of the longitude integrator are $\frac{-Vx}{R1}$, $-\cos\theta$, and $+\cos\theta$. The $\pm$ cosine of latitude inputs is supplied by cosine potentiometer R13B, on the latitude integrator shaft assembly. (The latitude integrator will be explained shortly.) The inputs to the longitude assembly cause the longitude motor to drive and, in turn, drive the longitude shaft. The longitude shaft positions the rotor of a synchro control transformer (CT). The output of the CT, which is proportional to the velocity input to the loop, is routed to a navigational computer.

Y-gyro torquing loop. The output of DC amplifier 3A4 is amplified in power amplifier 3A9 and applied to the Vx integrator. In the integrator, this signal is summed with the output of tangent potentiometer R17 to obtain total transport rate along the X-axis ($-$Vx). This signal is corrected by resistive network R1 and amplified in summing amplifiers 3A6. The output of the first section of 2A6 ($\frac{+Vx}{R1}$) is applied to sine potentiometer R18A and linear potentiometer R17. The output of the second amplifier section ($\frac{-Vx}{R1}$) is applied to sine potentiometer R18A and tangent potentiometer R17, to DC amplifier 3A5, and to assembly 3A17. Other inputs to summing amplifier assembly 3A17 are craft rate out of the 3A6 assembly ($\frac{-Vx}{R1}$), earth rate out of summing amplifier 3A16 ($-\Omega\cos\theta$), Y-gyro bias. The output of 3A17 (ω y) is applied to the Y-torquer coil of lower gyro YZ1. Gyro YZ1 is torqued until the sum of the X-accelerometer signal and X-accelerometer bias is zero.

Vy integrator circuit. The Y-velocity integrator provides $\pm$ Vy signals corresponding to aircraft velocity along the Y-axis. The Vy integrator circuit includes DC amplifiers 3A10 and 3A11, two power amplifiers 3A15, Vy integrator shaft assembly 3A24, and two summing amplifiers 3A12. Since the operation of the Vy and Vx integrators is almost identical, we will not explain completely the Vy integrator but merely point out how its operation differs. Inputs to 3A10 assembly are the differences between the two integrators. Inputs to 3A10 are Ay, Y-accelerometer bias, and centripetal and coriolis accelerations. The altitude correction is not used here. The craft rate input to assembly 3A12, Vy, has been corrected for the polar radius of the earth by resistive network R2 in the input of the summing amplifiers.

Latitude integrator circuit. The inputs to the latitude integrator, other than the Vx signals, are $\frac{+VY}{R2}$ and $\frac{-Vy}{R2}$. The output of the Vy integrator ($+$Vy) is corrected by resistive network R2 and amplified in summing amplifier 3A12. The output of the first section of 3A12 ($\frac{-Vv}{R2}$ is applied to sine potentiometer R18B. The output of the second amplified section $\frac{+Vv}{R2}$) is also applied to R18B and 3A11, and is summed with X-gyro bias to obtain Wx. The craft rate out of the second amplifier 3A12 is amplified by 3A11 and 3A15 assemblies and applied to the latitude integrator. This causes the latitude motor to drive the latitude shaft. The latitude shaft positions the rotor of a synchro control transformer. The output of the CT is proportional to the velocity input to the loop and is routed to a navigational computer. Potentiometers located on the latitude integrator generate tangent, sine, and cosine functions of latitude. Each of these will be explained later in this volume.

X-gyro torquing. The craft rate out of 3A12 ($\frac{+Vv}{R2}$) is summed with X-gyro bias and applied to the X-torquing coil of upper gyro XZ2. The input to the X-torquing coil precesses upper gyro XZ2 until the sum of the Y-accelerometer signal and the Y-accelerometer bias voltage is zero.

Z-gyro torquing. (See 3A18 at the upper middle of FO 2.) The Z1 torquing loop provides a signal to lower gyro YZ1 torque coil. The voltage of this signal is proportional to the combination of earth rate ($-\Omega$ sine ϕ), transport velocity ($\frac{-Vx}{R1}$ tan ϕ), and Z-axis gyro bias. Earth rate and transport velocity are computed in the latitude integrator and are applied as inputs to summing amplifier assembly 3A18, where they are combined with Z-gyro bias. The output of the summing amplifier, the Z1-axis torquing signal, is applied to lower gyro Z1-torquer coil. The upper gyro Z2-axis is caged to the lower gyro Z1-axis. The caging signal is developed in the caging amplifier portion of azimuth servo and caging amplifier assembly 3A2. The operation of this assembly in NAV is the same as in Af.

Vy integrator centripetal correction. The output of the Y-accelerometer must be corrected to eliminate undesirable accelerations, i.e., centripetal and coriolis. The centripetal correction signal is developed in R3. The arm of centripetal potentiometer R3 is controlled by the Vx integrator shaft. Voltages applied to R3 are $\frac{-Vx}{R1}$ tan ϕ and $\frac{+Vx}{R1}$ tan ϕ from summing amplifiers amplifiers 3A13. The output of R3 is $\frac{+Vx^2}{R1}$ tan ϕ. This voltage is the centripetal correction applied through 3A10 and 3A15 to the Vy integrator.

Vx integrator centripetal correction. Centripetal multiplier potentiometer R4 provides centripetal correction, $\frac{+VxVy}{R1}$ tan ϕ, for the Vx channel. Inputs to R4 are $\frac{-Vx}{R1}$ tan ϕ and $\frac{+Vx}{R1}$ tan ϕ from summing amplifiers 3A13. R4 is controlled by the Vy integrator shaft. A detailed explanation of these potentiometers will be presented later in this volume.

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Vy integrator coriolis corrections. The 3A6 summing amplifier assembly provides $\frac{+Vx}{R1}$ and $\frac{-Vx}{R1}$ signals for sine potentiometer R18A. R18A is located on latitude integrator shaft 3A24. The output of sine potentiometer R18A (2 Ω Vx sin ϕ) is the Vy coriolis correction applied to 3A10.

Vx integrator coriolis correction. The 3A12 assembly provides $\frac{+Vy}{-Vy}$ and $\frac{-Vy}{R2}$ signals for sine potentiometer R18B. R18B is located on latitude integrator shaft 3A24. The output of R18B (2Ω VY sin ϕ) is the Vx coriolis correction applied to assembly 3A4.

Vx integrator barometric correction. Barometric altitude for the INS is provided by an air data computer. Barometric altitude is applied through a differentiator located on the platform computer section, to assembly 3A4 as the altitude correction for the vertical component of coriolis. Figure 5-3 shows why altitude correction to the Vx channel is necessary.

Velocity output signals (Vn-s and Ve-w). The correct velocity outputs of the Vx and Vy integrators are applied to the navigational computer and to the latitude and longitude (displacement) integrators. The east-west velocity signals are taken from linear potentiometers on the end of each velocity integrator. The corrected velocity inputs to the displacement integrators are integrated with the appropriate corrections. A control transformer, mechanically connected to the longitude integrator shaft (3A24 in the upper right-hand corner of the navigator computer in foldout 2), provides the changes of longitude signals to the navigational computer. The latitude integrator (3A24 located in the center on the right-hand side of the computer) provides changes in latitude to the navigational computer. The navigational computer uses these input signals to provide a continuous readout of present latitude and longitude.

Exercises (633):

1. In the navigate mode, for what purpose do we use the true tangential velocity of the vehicle?

2. What signal is produced when the X-accelerometer signal and bias, vertical correction, centripetal, and coriolis accelerations are summed?

3. Where is the $-Vx$ signal corrected for the equatorial radius of the earth?

4. What causes the longitude integrator to integrate Vx proportional to the secant of latitude at high latitudes?

5. Where does the longitude integrator obtain the ± cos ϕ input?

6. When the longitude shaft positions the rotor of a synchro control transformer, to what is the transformer output proportional?

7. What does the output, $\frac{-Vx}{R1}$, from the second summing amplifier of the 3A6 assembly represent?

8. What does the output Ω cos ϕ, of the 3A16 assembly represent?

9. What signals does the Y-velocity integrator provide?

10. What is the function of resistive network, R2 at the input of summing amplifier 3A12?

11. In the navigate mode, how long does the input to the X-torquing coil precess upper gyro XZ2?

12. In the navigate mode what provides current to the lower gyro Z1 torquer coil that is proportional to the combination of $-\Omega \sin \phi$, $\frac{-Vx}{R1}$, + tan ϕ, and Z-axis gyro bias?

13. In the navigate mode, where are earth rate and transport velocity computed?

14. In the navigate mode, how is the upper gyro Z2 axis caged to the lower gyro Z1 axis?

15. What component provides the centripetal correction $\frac{Vx^2}{R1}$ tan ϕ?

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16. To what channel is centripetal correction $\frac{Vx^2}{R1}$ tan applied?

17. In the navigate mode, what are the inputs to centripetal potentiometer R4?

18. What is the function of R18A in the navigate mode?

19. What is the 2 Ω Vy sin ϕ correction?

20. What provides the barometric altitude for the INS?

21. What do the corrected velocity outputs drive?

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Detailed Analysis of the System

IN THE PREVIOUS chapter, we presented a description of an INS and a brief explanation of its operation. Having studied this information, you are now ready for the detailed block diagram analysis of an INS. This chapter contains a block diagram analysis of the power supplies, temperature control circuits, gimbal positioning servoloops, velocity and position integrating loops, and the gyro torquing loops.

6-1. Power Supply Block Diagram Analysis

Earlier, we discussed briefly the INS power supplies so that you could see how they relate to the system and the voltages they provided. Now refer to foldout 3 as you learn more about them. Let's start with the control circuits.

634. Trace the distribution of 115–VAC primary power and state the function of primary power control components.

Primary Power Control. Input power for the INS is provided by either the aircraft or an external power source. The input power is 115V, 400-Hz, 3-phase external power and aircraft 28 VDC. The external aircraft power A and B phase is applied to the INS environmental control and B phase to the power supply circuits. Next, you will see how the power is used when you select each mode.

Standby (STBY) mode. When you set the mode selector switch to STBY, the +28 VDC is applied through S1C to the coil relay of K22 (FO 3). K22 energizes and completes the path to ground through its contacts and the normally closed contacts of relay A25A1K8, to bridge rectifier 3A25A1CR4.

(NOTE: A25 is not shown on your diagram as part of the component number. You will find this true of most of the diagrams used in the remainder of this volume.

The 115V, 400-Hz, C-phase power is applied to rectifier bridge 3A25A1CR4 through contacts 4 and 5 of relay A1K1. Bridge 3A25A1CR4 rectifies the AC voltage and applies DC to relays 3A25A1K3 and 3A25A1K4, energizing them.

The relay coils are connected in series across the bridge rectifier through the INS interlock circuit. The INS interlock circuit interlocks the DC voltage applied to relays 3A25A1K3 and 3A25A1K4, through the connectors of each unit of the INS to insure that all the INS connectors have been properly mated and seated before power is applied to the units.

These relays apply 115V, 400-Hz, 3-phase power to the various power supply transformers. The transformers develop levels of AC voltage that are rectified, filtered, and regulated for use by the INS. When power supply relay 3A25A1K4 energizes, 115V, 400-Hz, B-phase is applied to diode 3A25A1CR3. This diode rectifies the AC and applies DC to an R–C network, which delays the output to 3A25A1K1 for approximately 200 milliseconds. This time delay allows the rectified +30 VDC and −30 VDC power supply to apply power to coil of relay 3A25A1K7. Assembly 3A21 applies ground to 3A25A1K7 energizing the relay and deenergizing 3A25A1K8. This relay is deenergized during normal INS operation. Whenever the outputs of the regulated +30 VDC or −30 VDC, the 28-VDC standby or the +28-VDC filtered power supplies fall below a specified level, 3A25A1K7 deenergizes, energizing 3A25A1K8. This removes ground from 3A25A1CR4 and removes 115V, 400-Hz, 3-phase power from the power supplies. Diode 3A25A1CR2 rectifies 115V, 400-Hz, C-phase power and energizes 3A25A1K5 and 3A25A1K6. These relays apply 115V, 400-Hz, 3-phase power to the ASN-63 OSDU.

ALIGN and NAV mode. When you set the mode selector to ALIGN, 3A25A1K1 and 3A25A1K2 are energized. These relays remain energized for 60 seconds and apply 140V, 400-Hz, 3-phase power to the gyro spin motors. At the end of 60 seconds, the output of the 60-second time delay circuits (3A8) energizes relay K27. This deenergizes relays 3A25A1K1 and 3A25A1K2 if the gyros are up to operating temperature. If the gyros are not up to operating temperature at the end of the 60-second time delay, relay K39 energizes and keeps relays 3A25A1K1 and 3A25A1K2 energized. When the gyros reach operating temperature, relay K39 deenergizes, deenergizing relays 3A25A1K1 and 3A25A1K2. The normally closed contacts of these relays apply 90V, 375-Hz, 3-phase precision power to the gyro spin motors.

Relay K28 is first energized in the ALIGN and NAV modes by +28-VDC coarse (Ac), which is applied to the relay through diodes A27CR21 and A27CR19. Ground is supplied through the normally closed contacts of deenergized relay K27. When K27 energizes after 60 seconds in ALIGN, a ground is supplied to K28 by the go/no-go circuit (3A8). Whenever the go/no-go circuit

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removes the ground (platform no-go condition) from relay K28, the relay deenergizes. When K28 deenergizes, it deenergizes K22, removing all power from the INS except heater power to the environmental controls in ALIGN.

Exercises (634):

1. What is the required voltage for the heaters used in the INS?

2. What is the function of relay 3A23K22 in the STBY mode?

3. Which phase voltage to the power supply transformers is controlled by relay 3A25A1K3?

4. What is the purpose of the interlock circuit in the INS?

5. In the ALIGN mode, what component provides ground for relays 3A25A1K1 and 3A25A1K2?

6. For what period of time is 140 VAC, 400-Hz, 3-phase power applied to the gyro spin motors?

7. What position must K27 be in to provide ground for relays 3A25A1K1 and 3A25A1K2?

8. What happens when K28 is deenergized as a result of a no-go signal in the ALIGN mode?

9. In what modes are relays 3A25A1K3 and 3A25A1K4 energized?

10. What purpose do A1R4, A1R12, A1C16, and A1C17 on assembly 3A25 serve?

11. With the proper input voltage, relay A25A1K7 energized, and A1CR4, A1K3, A1K4, and K22 good, what is the probable malfunction if there is no voltage on contacts 1 and 2 of relays 3A25A1K3 and 3A25A1K4?

12. What purpose do A1R3 and A1CR2 on assembly 3A25 serve?

635. Using a detailed block diagram, trace the development and distribution of the 4.5-kHz and 375-Hz gyro spin motor power supplies.

The 4.5-kHz Power Supply. During the Ac submode, the 4.5-kHz power supply illustrated in figure 6-1 provides a 15-VAC 4.5-kHz precision reference. This reference voltage is applied to the gyro and accelerometer pickoff excitation coils. A 115-VAC 4.5-kHz excitation voltage is also applied to the platform gimbal synchros. The power supply consists of regulator electronics and power supply assembly 3A21 and power supply assembly 3A25. The input to assembly 3A21 is generated by a 3-kHz tuning-fork type generator. This is applied to a frequency divider whose output of 1.5 kHz, is applied to a 4.5-kHz tuned amplifier. The 1.5 kHz is also used in the gyro spin motor power supply which is discussed later. From the amplifier, a 1.5-kHz signal is applied through a driver amplifier and a push-pull amplifier in assembly 3A25 to transformer 3A25T1. The outputs of the transformer are 115 VAC and 15 VAC at a frequency of 4.5 kHz.

Gyro Spin Motor Power Supply. The gyro spin motor power supply provides the gyro spin motors with precision 90-VAC 375-Hz, 3-phase power. This precision voltage is developed by gyro spin motor power supply assembly 3A20, regulator electronic and power supply assembly 3A21, and power supply assembly 3A25. Locate these assemblies in foldouts 3 and 4. Refer to these foldouts as we explain the gyro spin motor supply.

The input to assembly 3A20 is the 1.5-kHz signal we discussed above. In assembly 3A20, the 1.5-kHz signal is further divided by two frequency dividers. This supplies a 375-Hz signal to an amplifier and phase-shifting network that provides two 375 Hz signals with a phase difference of 90°. These two signals are applied through push-pull type power amplifiers to the power amplifiers in assembly 3A25. One power amplifier in 3A25 drives transformer 3A25T2, and the other drives transformer 3A25T3. These transformers provide a 3-phase,

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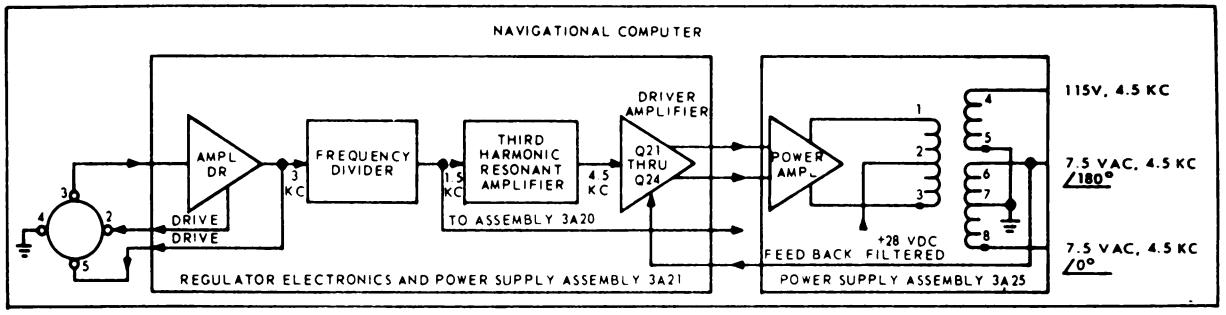

Figure 6-1. DC power supply.

90-VAC, 375-Hz output to the gyro spin motors through relays 3A25A1K1 and 3A25A1K2.

Exercises (635):

1. What is the source of the excitation voltage for the gyros, accelerometers, and synchros?

2. Refer to foldout 4. What does transformer T6 provide voltage for during Ac?

3. What is the difference between the input to transformers T2 and T3 in foldout 4?

4. Refer to foldout 4. What is the course of the 1.5-kHz input to assembly 3A20?

636. Using a detailed block diagram, trace the development of the +30, -30, +10, and -10 VDC power supplies.

Regulated +30 VDC and -30 VDC Power Supply. The +30- and -30-VDC power supply consists of assemblies 3A21 and 3A25, which are shown in figure 6-2. The outputs of this power supply are used throughout the INS as transistor bias voltage. Three-phase, 115-VAC 400-Hz power is applied to transformer 3A25T6 through power supply relays 3A25A1K3 and 3A25A1K4. The outputs of transformer T6 are rectified and filtered, and the resulting +15 and +45 VDC are applied to transistors 3A25Q8 and 3A25Q7 respectively.

The +30-VDC regulator circuit consists of transistors 3A25Q7 and 3A21Q1 through 3A21Q4. This circuit drops 15 volts of the +45-VDC input and, at the same time, provides a +30-VDC signal which controls the output of Q7. The output of Q7, +30 VDC, is applied to the INS. The -30-VDC regulator circuit consists of transistors 3A25Q8 and 3A21Q5 through 3A21Q8. This circuit drops the +15-VDC input; however, because this circuit is referenced to -30 VDC instead of ground, the resultant output of trnsistor 3A25Q8 is -30 VDC to the INS.

Precision +10 VDC and -10 VDC Power Supply. The +10- and -10 VDC power supply shown in figure 6-3 consists of electrical component oven assembly 3A22, summing amplifier assembly 3A19, integrator shaft assembly 3A24, and power supply assembly 3A25 (shown on foldout 3). Interconnection between assemblies is also illustrated in figure 6-3. The +10- and -10-VDC outputs are used by the INS as gyro and accelerometer reference voltages. These precision voltages are also used as reference voltages for computing mechanisms (nonlinear potentiometers, capacitance tachometers, etc.) in the navigational computer.

Regulated +30 VDC is applied across voltage dropping resistors A1R26 and A1R25 to resistor A1R24 in assembly 3A22. The voltage at the junction of the voltage dropping resistors is regulated to approximately +9.5 VDC by zener diode A2CR1. The voltage at the wiper arm of potentiometer A1R24 is applied to a summing amplifier in assembly 3A19. The summing amplifier is a unity gain amplifier

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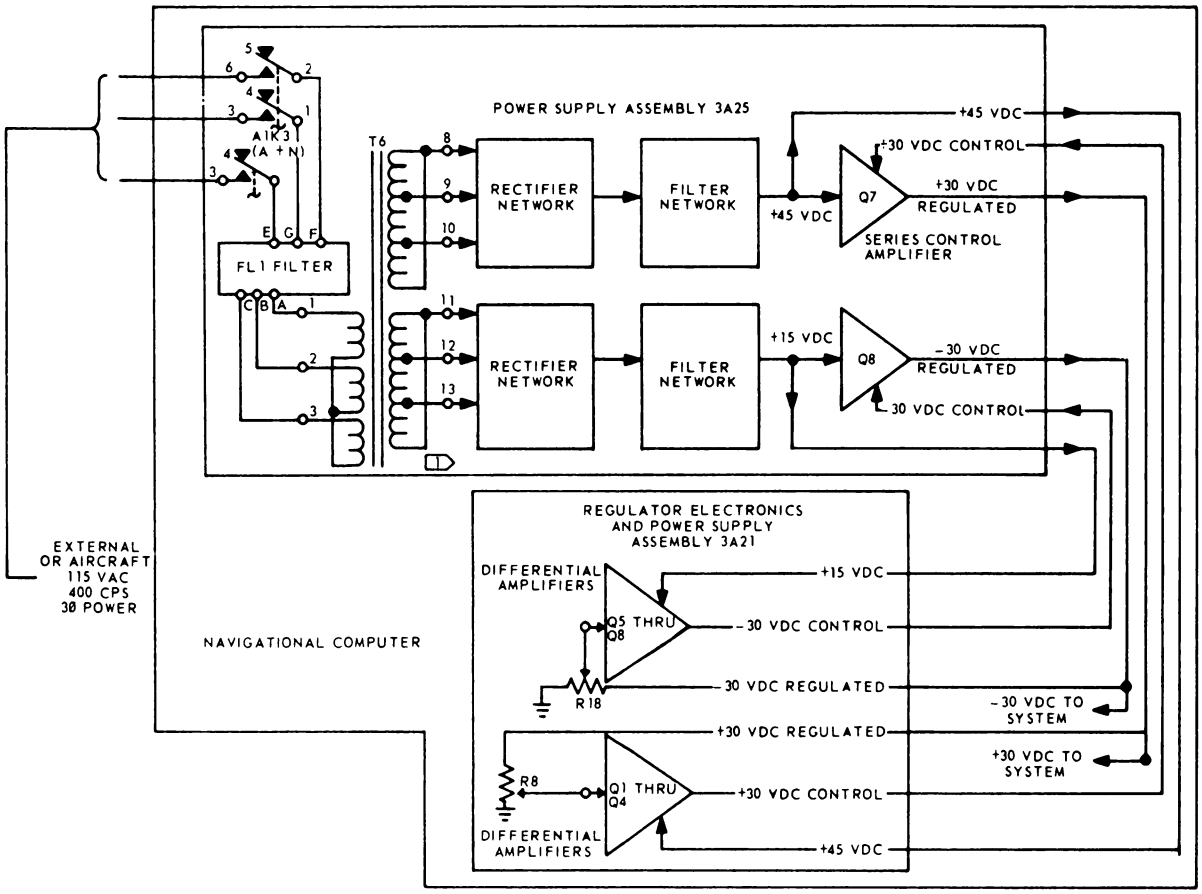

Figure 6-2. Regulated +30- and -30-VDC power supply.

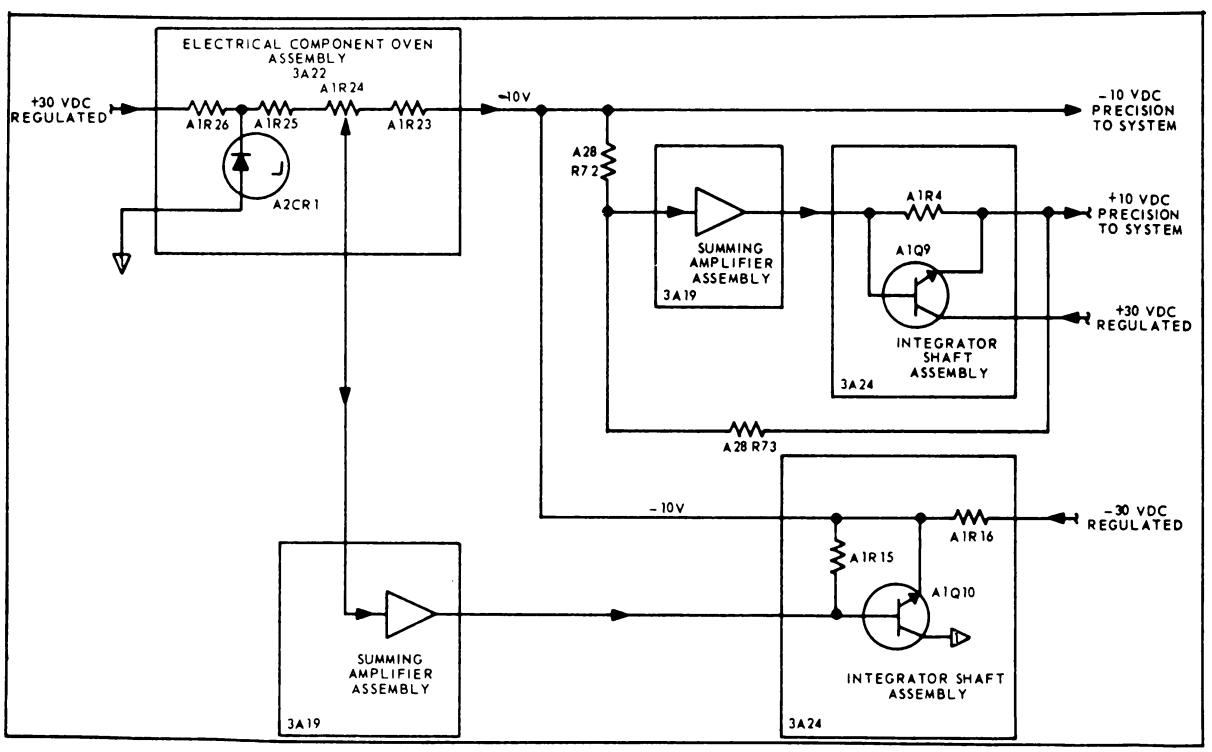

Figure 6-3. Precision +10- and -10-VDC power supply.

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that reverses the polarity of the input voltage. The output of the summing amplifier is applied to a shunt regulator in assembly 3A24. The output of the regulator is precision -10 VDC.

Regulated +30 VDC is also applied to a series regulator in assembly 3A24. This regulator drops the +30 VDC to +10 VDC that is applied to the input of a summing amplifier in assembly 3A19. Also, -10 VDC is applied to the input of the same summing amplifier. If the series regulator drops the +30 VDC to exactly +10 VDC, the resultant input to the summing amplifier is zero volts. If the series regulator does not drop the +30 VDC to exactly +10 VDC, the input to the summing amplifier in 3A19 is an error signal. The summing amplifier reverses the polarity of the error signal and applies it to series regulator A109, compensating the regulator output for +10 VDC.

OSDU Power Supply. This supply is illustrated in figure 6-4 and foldout 3. The input to the OSDU power supply is 115-VAC, 400-Hz, 3-phase external or aircraft power. This power is applied to transformer T1 through power supply relays 3A25A1K5 and 3A25A1K6. One output of transformer T1 is rectified unfiltered +30V, supplied as power amplifier collector supply voltage to true heading ground track servoamplifier 2A1. Other outputs of transformer T1 are 13V 0-degree, 26V 90-degree, 22V 0-degree, 13V 90-degree, and 6.3V 75-degree signals. The 13V 0-degree signal is used as a generator and demodulator reference voltage and control transformer and resolver excitation in assembly 2A1 and climb angle and drift correction angle servoassembly 2A2. The 22V 90-degree signal is applied to the drift correction angle servoamplifier 2A2AR2 pulse former. The 26V 90-degree signal is used as motor excitation voltage in assembly 2A1 and generator reference voltage in assembly 2A2. The 13V 90-degree signal is applied as a 400-Hz modulating voltage to air valve servoamplifier and transient detector 2AR1. The 6.3V 75-degree signal is applied as chopper excitation voltage to the DC amplifiers and summing amplifiers.

Exercise (636):

1. What assembly provides the voltage used as transistor bias in the INS?

2. Refer to figure 6-2. What is the +30-VDC output of 3A21Q1 through 3A21Q4 used for?

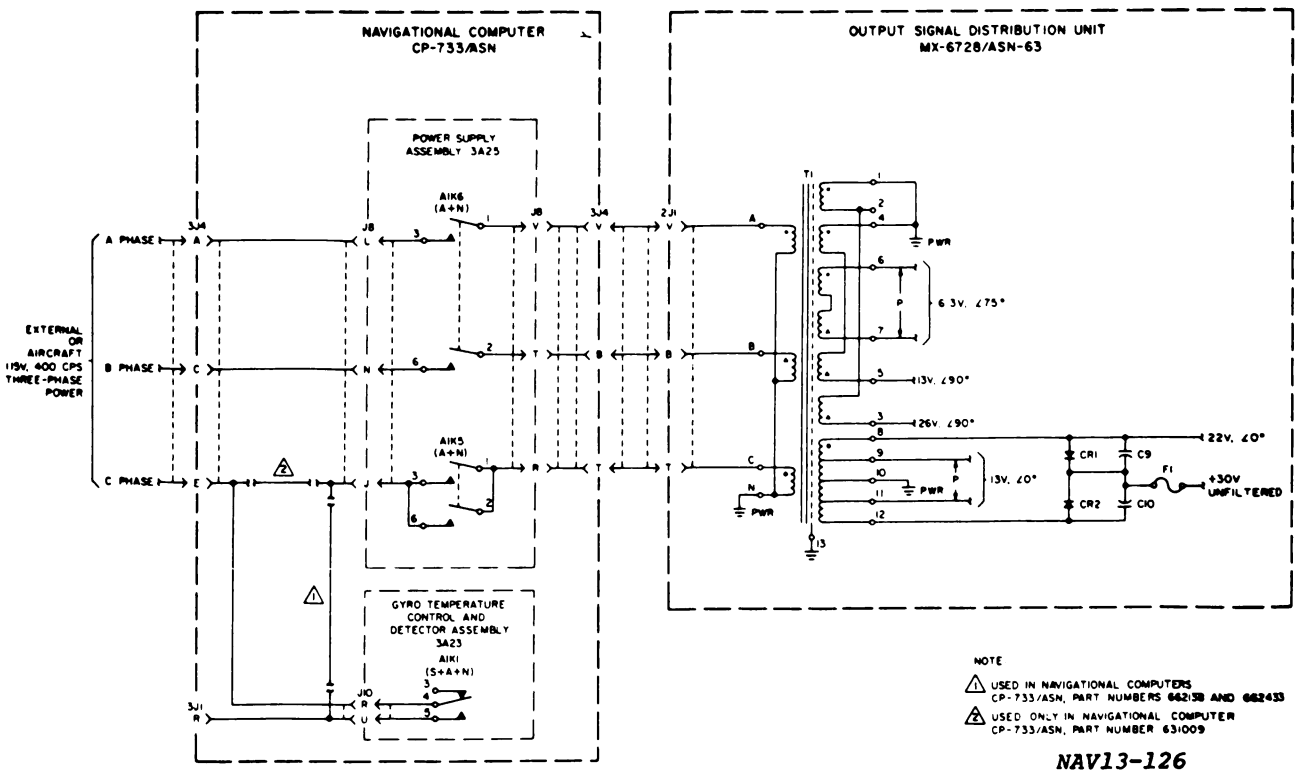

Figure 6–4. OSDU power supply, functional diagram.

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3. What is the purpose of the precision ±10 VDC?

4. In figure 6-3, what is the function of 3A22A2CR1?

5. In figure 6-3, what happens if series regulator 3A24A1Q9 does not drop the +30 VDC to exactly +10 VDC?

6. Refer to figure 6-4. For what purpose are the outputs of transformers T2 and T3 used?

6-2. Temperature Control Circuits

Accuracy of the INS is insured by maintaining the platform ambient temperature between 123° F. and 133° F., the temperature of the gyros and accelerometers between 158° F. and 162° F., and the temperature of the navigational computer oven at 158° ± 4° F. The four separate temperature control loops that maintain these temperatures within the specified limits are the ambient temperature, upper gyro temperature, lower gyro temperature, and platform servovalve temperature loops. Each of these control loops independently senses the operating temperature and compensates for variations. In addition, a controlled temperature environment is provided for the precision resistors, capacitors, potentiometers, and a zener diode in computer electrical component oven assembly 3A22.

Let's see how the input and control voltages are supplied to the temperature control circuits. Earlier in this chapter, we stated that relay 3A23A1K1 controls the voltage inputs to the system environmental control circuits (see left side of foldout 5). When you set the mode selector switch on the unit control to STBY, ALIGN, or NAV, 115-VAC, 400-Hz, ϕB power is applied through pin 10 of S1D to relay A1K1. When A1K1 is energized ϕA voltage is applied through pins 13 and 14 of A1K1 to blower motor B1, the ambient, upper gyro, and lower gyro heater control circuits. The ϕB voltage is applied through relay pins 10 and 20 to pins 11 and 19 respectively. From pin 19 of A1K1, ϕB voltage is applied to blower motors B1 and BB1, FL4, assembly 3A22, and ambient heaters HR7, HR8, and HR9. From pin 11, the ϕB voltage is applied to the gyro temperature detector to T6 and through S1 to HR1, HR2, HR5, HR10, HR11, and HR12. It is also applied through S2 to HR3, HR4, and HR6. Now that we have the necessary voltages to the temperature control loops, continue to refer to foldout 5 as you study these loops further.

637. Using a detailed block diagram, trace the four ambient temperature control loops.

Platform Ambient Temperature Control Loop. The platform ambient temperature control loop consists of heaters HR7 through HR9, thermistors R10 and R12, 165° thermostat S3 (mounted inside the platform), and an amplifier and control circuit in gyro temperature control and detector assembly 3A23.

The output of 3A23T6 is applied to the input of the ambient heater control and through a rectifier regulator and filter circuit to an 8-Hz relaxation oscillator. The output of ambient thermistors R10 and R12 and the 8-Hz relaxation oscillator output are applied to the temperature sensing amplifier where the phase relationship is compared. The output of the temperature sensing amplifier gates the ambient heater control circuit. The gating of the ambient heater control circuit determines the amount of current flow through the ambient heaters. As the thermistor input to the temperature sensing amplifier varies due to changes in ambient temperature, the output of the temperature sensing amplifier varies proportionally and thus regulates the current flow through the ambient heaters. If the platform ambient temperature rises above 165° F. due to a circuit malfunction, thermostat S3 opens and removes the 115-Vac ϕB heater power from the ambient heaters.

Gyro Temperature Control Loops. The upper gyro temperature control loop and the lower gyro temperature control loop operate the same as the platform ambient temperature control loop. Therefore, we will only identify the components in each loop.

The upper gyro temperature control loop consists of heaters HR1, HR2, HR5, HR10 through HR12, thermistors R1 and R2, 185° thermostat S1, amplifiers A1Q7 through A1Q12, and the heater control circuit. Two heaters are mounted on the gyro endbells, one

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on each accelerometer, and one heater is mounted on the upper gyro mounting plate.

The lower gyro temperature control loop consists of heaters HR3, HR4, HR6, thermistors R1 and R2, 185° thermostat S2, amplifiers A1Q13 through A1Q18, and the heater control circuit. The three gyro heaters are mounted the same as the upper gyro heaters.

Platform Servovalve Temperature Control Loop. The platform servovalve temperature control loop consists of thermistors R3 and R13, an air valve servoamplifier (located in the OSDU), valve motor BM9, and a servo-controlled air valve. The platform cover consists of two concentric ball-shaped shells separated by an air duct. The duct allows cooling air to circulate about the inner shell of the platform and helps to stabilize the platform temperature.

When you set the mode selector switch to ALIGN or NAV, the output of the series-connected thermistors and the output of the valve potentiometer are applied to the air valve servoamplifier in assembly 2A1 (in the OSDU). The two inputs are compared by a summing amplifier. The output of the summing amplifier is applied through modulator Q7, power amplifier Q8-Q14, to valve motor BM9, which, in turn, drives the air valve and the wiper arm of the valve potentiometer. The output of the valve potentiometer is fed back to the summing amplifier. The normal temperature control point of the loop is 123° F. Any deviation from this specified temperature is sensed by the thermistors, and the resulting output controls the air valve through BM9. This action maintains the normal operating temperature by controlling the amount of cooling air circulated about the platform.

Electrical Component Oven Temperature Control Loop. The electrical component oven temperature control loop (assembly 3A22) consists of control thermostat S1, booster thermostat S2, HR1, and HR2. This loop provides environmental temperature control for electrical component oven assembly 3A22. Recall that 3A22 contains precision resistors, capacitors, potentiometers, and a zener diode.

When you set the INS to any mode other than OFF, thermostat S1 closes and 115-VAC, 400-Hz, ϕB aircraft power is applied to the 20-watt heating element. Thermostat S2 controls the 10-watt heating element in series with thermostat S1, so that both thermostats must be closed to energize the 10-watt element. If the electrical component oven temperature rises above the desired temperature, the thermostats open and remove the ϕB power from both heaters. The temperature control oven heaters operate independently of and are not affected by the platform heating circuits. If the temperature falls below 145°, both thermostats close, applying 30 watts to heat the assembly.

Exercises (637):

1. In the STBY mode, what position must 3A23A1K1 and 3A25A1K4 be in before power is available to the environmental control circuits?

2. What determines the amount of current flow through the ambient heaters?

3. What does the sensed output of thermistors R3 and R13 control?

4. What controls the heaters in the electrical component oven?

5. Refer to foldout 5. At what temperature will S3 open?

6. What does the gating of the ambient heater control circuit do?

6-3. Gimbal Positioning Servoloops

The gimbal servoloops maintain the initial stable element alignment. These loops are the azimuth, pitch, inner roll, and outer roll servoloops. Refer to the referenced foldout as we discuss each loop. Also locate, on foldout 1, the loop being discussed. This will give you an overall picture of just how the loop ties into the complete system.

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638. Using a detailed block diagram, trace the azimuth servoloop and cite the origin of the correction signals.

Azimuth Servoloop. In our discussion of the azimuth servoloop, use foldout 6 to trace the signal. In the ALIGN mode, a true north signal from an associated navigational computer is applied to control transformer B3 (see upper right of the OSDU). The true north signal is sensed by rotor R2 of control transformer B3 and applied through contacts 3 and 1 of relay A2K2 to an AC amplifier in assembly 2A1. The output of the AC amplifier is applied to MG1. MG1 drives the true heading shaft that, in turn, positions the rotor of control transformer B2. During the Ac mode, when the angular position of the stable element and the angular position of the OSDU true heading shaft are not in coincidence, a 4.5-kHz signal is sensed by rotor R1 of control transformer B2 (see upper left of the OSDU). The sensed 4.5-kHz signal, which represents the error between true north and the azimuth orientation of the stable element, is applied to assembly 2A1. This is the azimuth servoamplifier that consists of an AC amplifier, a demodulator, and a 4.5-kHz modulator. The output of the 4.5-kHz modulator is applied through contacts 1 and 3 of relay A28K23 to azimuth servoamplifier assembly 3A2. The 3A2 consists of an AC amplifier, a demodulator, a DC amplifier, a modulator, and a driver amplifier. The outputs of the driver amplifier are applied through a power amplifier in assembly 3A24 to the control windings of azimuth gimbal servomotors BM1 and BM2. These motors drive the stable element until the output of rotor R1 of control transformer B2 is zero. This indicates that the angular position of the stable element and the angular position of the OSDU true heading shaft are in coincidence.

An antibacklash voltage, 5.8 VAC 400 Hz, is also applied to the control windings of the azimuth gimbal servomotors to eliminate servo-gear train backlash.

During the Af and NAV modes, the Z1 pickoff coil (lower gyro YZ1) output is used to position the stable element. The Z1 pickoff signal is applied to the azimuth servoamplifier, consisting of an AC amplifier, a demodulator, a DC amplifier, a modulator, and a driver amplifier in assembly 3A2. The output of the driver amplifier is applied through the power amplifier in assembly 3A24 to the azimuth gimbal servomotors. The pickoff signal causes the servomotors to drive the stable element until the 1 pickoff signal is zero.

A 4.5-kHz signal from the upper gyro XZ2 pickoff coils is applied to the azimuth caging amplifier, consisting of an AC amplifier, a demodulator, and a DC amplifier in assembly 3A2. The output of the DC amplifier is applied to the Z2 torquer of upper gyro XZ2 to cage the upper gyro to itself.

Exercises (638):

1. During Ac, if the stable element and the OSDU true heading shaft are not at the same angular position, where does the signal originate to correct this?

2. Where is a signal applied to the azimuth servoloop to eliminate backlash?

3. Where does the signal come from to cage the upper gyro to itself?

4. During Af, where does the signal come from in the azimuth servoloop to position the stable element?

639. Using a detailed block diagram, trace the pitch servoloop and cite the origin of the correction signals.

Pitch Servoloop. During Ac, 115-VAC 4.5-kHz excitation voltage is applied to pitch synchro BCX3 (see foldout 7). The stator output of BCX3 is applied through A28K23 to pitch servoamplifier 3A3. The pitch servo section consists of an AC amplifier, a demodulator, and a DC amplifier. In the energized state, relay K6 shorts out capacitor C18, allowing the DC amplifier to operate as a high-gain linear amplifier. The output of the DC amplifier is applied through filter A27FL1 to the pitch servo section of 3A3. This section consists of a 400-Hz modulator and a DC amplifier. The outputs of the DC amplifier are applied through push-pull amplifiers in assembly 3A24

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to the control winding of pitch gimbal servometers BM5 and BM6. As these motors drive, they position the pitch gimbal until BCX3 is nulled. At this time, the pitch gimbal is caged to the aircraft attitude.

During AF and NAV, 15-VAC 4.5-kHz voltage is applied to the primary of lower gyro Y-pickoff coil. Misalignment between the pitch gimbal and the horizontal reference is sensed by the secondary of the lower gyro Y-pickoff coil. The sensed error signal is amplified by Y-gyro preamplifier Q1 and Q2, then applied to R1 of azimuth resolver BR1. The resolved output is applied to the pitch servo section of 3A3 and through filter A27FL1 to BM5 and BM6 as described above in Ac. In Af and NAV, the servomotors drive the pitch gimbal until the sensed output of the secondary of the lower gyro Y-pickoff coil is zero.

Note that in NAV the output of BCX3 is applied to a pitch angle detector. The operation of this control loop for BCX3 will be discussed later in this section.

Exercises (639):

1. During Ac, where does the signal originate to level the pitch gimbal?

2. During Af and NAV, where does the signal originate to level the pitch gimbal?

3. Which stator output of BCX3 is applied to the 3A3 assembly during coarse align?

4. During Af and NAV, when do the pitch gimbal servomotors stop driving?

640. Using a detailed block diagram, trace the inner roll servoloop and cite the origin of the correction signals.

Inner roll Servoloop. During Ac, 115-VAC 4.5-kHz excitation voltage is applied to inner roll synchro BCX2 (see foldout 8). The stator output of BCX2 is applied through A28K24 to the inner roll servo section of 3A3. This section consists of an AC amplifier, a demodulator, and a DC amplifier. The outputs of the DC amplifier are applied through a push-pull amplifier in assembly 3A24 to the control windings of inner roll gimbal servomotors BM3 and BM4. BM3 and BM4 position the inner roll gimbal until inner roll synchro BCX2 is nulled. At this time, the inner roll gimbal is caged to aircraft attitude.

In Af and NAV, a 115-VAC 4.5-kHz signal is applied to the primary of upper gyro X-pickoff coil. Any misalignment between the inner roll gimbal and the vertical reference is sensed by the secondary of the upper gyro X-pickoff coil. The sensed error signal is amplified in X-gyro preamplifier Q1 and Q2 and applied to R2 of azimuth resolver BR1. The resolved output of BR1 is applied to the inner roll servo section, consisting of an AC amplifier, a modulator, and a DC amplifier in assembly 3A3. The output of the DC amplifier is applied through filter A27FL2 to the inner roll servo section of 3A3. This section consists of a 400-Hz modulator and an AC amplifier. The AC amplifier's outputs are applied through a push-pull amplifier in assembly 3A24 to the control windings of the inner roll gimbal servomotors BM3 and BM4. These motors drive the inner roll gimbal until the sensed output of the upper byro X-pickoff coil (secondary) is zero or the inner roll gimbal is aligned with the vertical reference.

Exercises (640):

1. In Ac, where does the signal originate to position the inner roll gimbal?

2. Which pickoff coil senses misalignment between the inner roll gimbal and the vertical reference?

3. What is synchro BCX2 caged to when nulled during Ac?

4. Where is the amplified error signal from the upper gyro X-pickoff coil applied?

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641. On a detailed block diagram, trace the outer roll servoloop and cite operational techniques.

Outer Roll Servoloop. The outer roll servoamplifier consists of a linear channel and a rate (nonlinear) channel. The linear channel controls the outer roll gimbal servodrive during normal operation of the system. Recall that the inner roll gimbal prevents gimbal lock that would cause the stable element to "tumble." To avoid gimbal lock, the outer roll axis torquer is controlled by a pickoff on the inner roll axis to maintain the azimuth axis perpendicular to the pitch axis at all times. (Look back at fig. 4-9.) When the aircraft attitude exceeds 90° of pitch angle, the outer roll gimbal is rotated through 180° (fig. 4-9,C). This "flipping" action is accomplished by the rate channel. Initially, during the flip, the rate channel provides gimbal torque in the direction of rotation; as the flip is completed, the rate channel reverses the gimbal torque, thus acting as a brake to the rapidly rotating gimbal. The flipping operation occurs with a maximum rate rotation and a minimum rotational overshoot. The outer roll to inner roll gimbal coupling is a function of pitch attitude; thus, a nonlinear gain network must be used to vary the gain of the linear servoamplifier relative to the pitch angle of the aircraft. Note in assembly 3A1, foldout 9, that the proportional amplifier channel consists of a preamplifier, a nonlinear demodulator, and an operational amplifier. The rate channel consists of a demodulator and a differential operational amplifier. Both channels are summed into a cascaded 400-Hz modulator and power amplifier. Use foldout 9 to trace the signal as we discuss the operation of the outer roll servoloop.

During Ac and Af, the 115-VAC 4.5-kHz signal is applied to outer roll synchro BCX4 and pitch synchro BCX3. (In the NAV mode, BCX4 and BCX3 receive 115-VAC, 400-Hz, ϕ C excitation.) The stator output of BCX4 is routed through contacts 3 and 1 of relay A28K24 to the linear channel of the outer roll servoamplifier described above. The outputs of AC amplifier Q14 through Q18 are applied to a push-pull amplifier in assembly 3A24. The outputs of assembly 3A24 are applied to the control windings of outer roll gimbal servomotors BM7 and BM8, which drive the outer roll gimbal until the sensed output of outer roll synchro BCX4 is zero. During Af and NAV, the stator output of BCX4 is applied to the OSDU as roll information for associated avionics.

During the NAV mode, the stator output of inner roll synchro BCX2 is applied through pins 4 and 1 of relay A28K24 to both channels of the outer roll servoamplifier in assembly 3A1 described above. Inner roll synchro BCX2 is excited by a 15-VAC 4.5-kHz signal from power supply assembly 3A25. The stator output of pitch synchro BCX3 is applied to the pitch angle detector in go/no-go, pitch angle detector, time delay, and flasher assembly 3A8. The output of the pitch angle detector is applied to the linear channel of outer roll servoamplifier assembly 3A1. The gain of 3A1 now becomes a function of the pitch angle. The output of 400-Hz modulator Q13 is routed through an AC amplifier and applied to a push-pull amplifier in assembly 3A24. The outputs of assembly 3A24 are applied to the control windings of the outer roll gimbal servomotors BM7 and BM8. These servomotors drive outer roll gimbal BCX4 until the sensed output of BCX4 is zero.

Exercises (641):

1. Which channel controls the outer roll gimbal servodrive during normal operation of the INS?

2. Since the outer roll to inner roll gimbal coupling is a function of pitch attitude, what type of gain network must be used to vary the gain of the linear servoamplifier relative to the angle of the aircraft?

3. During Af and NAV, what does the output of BCX4 represent, and where is this output used?

4. In the NAV mode, why is the output of assembly 3A8 applied to assembly 3A1?

5. Which channel accomplishes the "flipping" of the outer roll gimbal?

6. Refer to foldout 9. Where is the output of the pitch angle detector applied?

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6-4. Velocity and Position Integrating Loops

Recall, from our discussion in Chapter 5, that the INS uses four electromechanical integrators to solve navigation problems. These are the Vx, Vy, latitude, and longitude integrators. Each electromechanical integrator consists of a DC amplifier, summing amplifier, power amplifier, capacitance tachometer switch, motor, shaft, and various output devices such as synchro control transformers and potentiometers. The output devices are geared to the shaft which is driven by the motor.

642. State the purpose of the capacitance tachometer.

Tachometer. In Volume 1, you studied all the components of the electromechanical integrator except the capacitance tachometer. Locate capacitance tachometer switch S2 in foldout 10. Note that it is composed of three segments and a wiper arm. Segment B3 is connected to a positive voltage, segment B1 is connected to a negative voltage, and segment B2 provides the output. The wiper arm is connected to an LC network in component oven assembly 3A22. As the wiper arm rotates, capacitor A2C1 is charged first positive, then negative, or—depending on the direction of rotation—first negative, then positive, and then discharged. The discharge occurs when the wiper arm touches the output segment and results in a series of positive or negative pulses. Inductor A1L1 is connected to the wiper arm as an arc suppressor.

Exercises (642):

1. In foldout 10, what is the purpose of 3A22A2C1, which is connected in series with the wiper arm of S2?

2. What is the purpose of inductor A1L1?

643. On a detailed block diagram, trace the Vx and Vy velocity integrator loops.

Vx Integrator Loop. All the inputs to this integrator are summed at the input to DC amplifier 3A4 (see left center of foldout 10). These inputs are the platform X-accelerometer bias voltage, which compensates for the inherent X-accelerometer error; barometric altitude from the air data computer (in the NAV mode); Ax from platform X-accelerometer (except in Ac); centripetal acceleration from resistor 3A24R4; coriolis acceleration from resistor 3A24R18B; and feedback voltage from capacitance tachometer 3A24S2 (in the NAV mode).

During ALIGN, relay A25K2 is energized. In the energized state, pins 1 and 3 short across capacitor A25C2, allowing DC amplifier assembly 3A4 to operate as a high-gain amplifier. The output of DC amplifier assembly 3A4 and the output of resistor 3A24R1A are applied to summing amplifier assembly 3A6. The +V-velocity signal output of 3A6A is routed to associated avionics, assembly 3A9, and latitude integrator R18A. The outputs of assembly 3A9 are applied to motor 3A24B3, which drives the Vx shaft. To obtain -Vx, the output of amplifier 3A6A is routed through A26R37 to the input of 3A6B. The output of 3A6B is applied to latitude integrator R18A and, as -X-velocity signal, to associate avionics.

During the NAV mode, relay 3A26K2 is deenergized. In the deenergized state, pins 1 and 4 close, removing the short circuit across capacitor 3A26C2 and allowing DC amplifier assembly 3A4 to operate as a low-gain amplifier. The output of 3A4 is now applied directly through assembly 3A9 to motor 3A24B3. During ALIGN and NAV, relay K1 is energized. In the energized state, relay K1 disconnects resistor 3A26R7 from the input of DC amplifier assembly 3A4, removing the degenerative feedback signal.

The function of this integrator loop is to drive motor 3A24B3 in a direction and amount corresponding to east-west velocity. The outputs are ±Vx from assembly 3A6 and velocity east-west from 3A24R1B, which is driven by motor B3. The voltage from the wiper of resistor 3A24R1B is east-west velocity signal for the associated computer and avionics.

Vy Integrator Loop. All the inputs to this integrator are summed at the input to 3A10 (see left center of foldout 11). These inputs are platform Y-accelerometer bias voltage, which

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compensates for the inherent Y-accelerometer error; Y-acceleration from the Y-accelerometer; centripetal acceleration at the junction of resistors A27R21 and A27R22 (see above assembly 3A12); coriolis acceleration from 3A24R18A; and the Y-velocity feedback signal from capacitance tachometer 3A24S3 (in the NAV mode).

During ALIGN, relay A27K5 is energized. When this relay is energized, pins 1 and 3 bypass capacitor A27C4, allowing DC amplifier assembly 3A10 to operate as a high-gain amplifier. The output of the DC amplifier and the voltage from the wiper of resistor 3A24R2A (see right center of foldout 9) are applied to assembly 3A12. The output of 3A12A is routed to assembly 3A15, R18A, and to associated computer and avionics as -Y-velocity signal. The output of 3A12A is applied through 3A12B to obtain +Vy, which is also applied to R18A and as an output to associated computer and avionics. The outputs from 3A15 are applied to motor 3A24B4, which drives the Vy shaft, and as feedback through relay A27K12.

During the NAV mode, relay A27K5 is deenergized, removing the short across capacitor A27C4 and allowing DC amplifier assembly 3A10 to operate as a low-gain amplifier. The DC amplifier output is now applied directly through power amplifier assembly 3A15 to motor 3A24B4, which drives the Vy shaft. During ALIGN and NAV, relay K1 is energized. When energized, relay K1 disconnects resistor 3A27R30 from the input of DC amplifier assembly 3A10, removing the degenerative feedback signal.

The function of this integrator loop is to drive motor 3A24B4 in a direction and amount corresponding to north-south velocity. The outputs are ±Vy from assembly 3A12, and velocity north-south from 3A24R2B, which is driven by motor B4. The output from the wiper of resistor 3A24R2B is north-south velocity signal for the associated computer and avionics.

Exercises (643):

1. In foldouts 10 and 11, why is accelerometer bias applied as an input to assembly 3A4?

2. In foldouts 10 and 11, what type of amplifier is 3A4 when operating in the NAV mode?

3. In foldouts 10 and 11 and in the NAV mode, what is the function of relay K1?

4. In foldout 10, what does the signal from the wiper of 3A24R1B represent?

5. In foldout 11, why is the output of summing amplifier 3A12A applied to summing amplifier 3A12B?

6. In foldout 11, what components does motor 3A24B4 drive?

644. Using a detailed block diagram, trace the latitude and longitude integrator loops.

Latitude Integrator Loop. In the NAV mode, +Vy is applied from the Vy integrator to DC amplifier 3A11 (see the left side of foldout 12). Capacitance tachometer 3A24S4 applies a feedback signal to resistor 3A22A1R3 through A4K2 (deenergized). From the junction of the two resistors, the resulting velocity signal is applied through 3A11, the normally open contacts (pin 6) of relay K17, and power amplifier assembly 3A15 to motor 3A24B5. Motor B5 positions the latitude shaft.

The latitude shaft positions the wiper arms of potentiometers A324R17, 3A24R13A, and 3A24R13B, and drives control transformers B6 and B7. The potentiometers generate tangent, sine, and cosine functions, respectively, of latitude. In ALIGN, since there is no velocity loop (relay 3A26K10 energized), the only input to power amplifier assembly 3A15 is present position data from the latitude demodulator in assembly 3A24. The operation of B6, B7, and the two-speed switching network will be explained in Chapter 7.

Longitude Integrator Loop. The operation of the longitude integrator loop illustrated in foldout 13 is similar to that of the latitude loop. In the NAV mode, -Vx from the Vx integrator is summed at the junction of resistors 3A22A2R6 and 3A22A1R4, with feedback output from capacitance tachometer 3A24S1. The resulting velocity signal is applied through DC amplifier assembly 3A5 and power amplifier assembly 3A9 to motor 3A24B1. The motor

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drives the longitude shaft that positions the rotor of synchro control transformer 3A24B2. The rotor output of the synchro, which is proportional to the velocity input to the loop, is applied to the associated computer and avionics. During ALIGN, the only input to power amplifier assembly 3A9 is present position longitude from the longitude demodulator in assembly 3A24. The control transformer and the longitude demodulator will be discussed in detail in Chapter 7.

Exercises (644):

1. In the NAV mode (foldout 12), the velocity signal from 3A11 is applied to assembly 3A15 through which contacts of relay K17?

2. In ALIGN (foldout 12), what is the input to assembly 3A15?

3. What relationship does the rotor output of synchro control transformer B2 have to the velocity input to the loop?

4. Where is the Vx integrator signal -Vx summed?

5. What input is applied to assembly 3A9 during align?

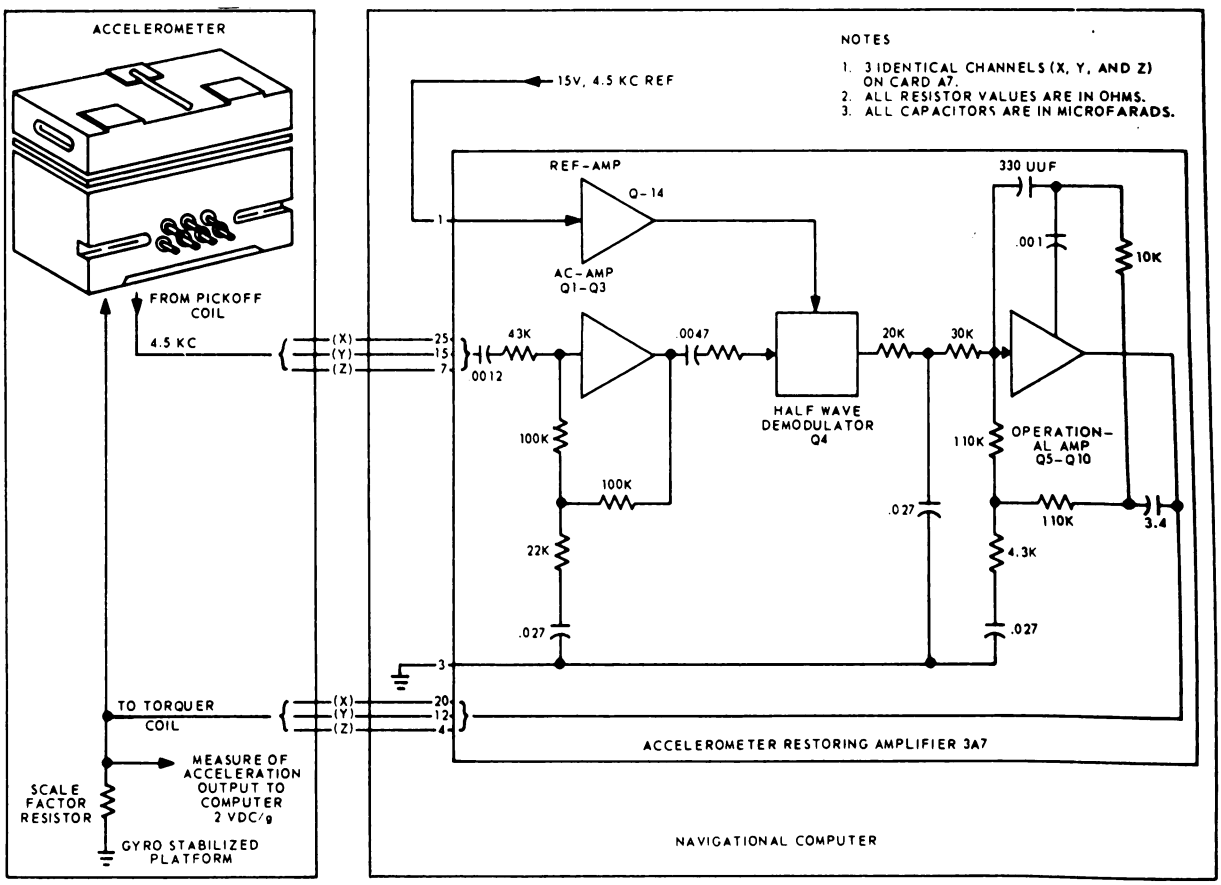

Figure 6-5. Accelerometer restoring loop.

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645. Using a detailed block diagram, cite operational characteristics of the accelerometer restoring loops.

Accelerometer Restoring Loops. Three separate accelerometer restoring loops are used to reposition the three floated pendulous elements of the X-, Y-, and Z-accelerometers. The accelerometers must be repositioned whenever a displacement of the element occurs that is due to an acceleration. Since the three accelerometer restoring loops are identical, only the X-axis accelerometer restoring loop is described.

The X-accelerometer restoring loop is shown in figure 6-5. The 4.5-kHz pickoff error signal is amplified by the AC amplifier in the accelerometer restoring amplifier assembly 3A7 in the navigational computer. The output of the AC amplifier is applied to the demodulator together with a 4.5-kHz reference signal. The DC signal out of the demodulator has a polarity dependent on the phase difference between the 4.5-kHz reference signal and the input from the AC amplifier. The output of the DC amplifier is applied to a high-gain, feedback-stabilized power amplifier whose frequency response is designed to accommodate the varying 4.5-kHz pickoff error signal of the X-accelerometer. The power amplifier also provides a feedback gain control for the DC amplifier. The power amplifier output is applied to the X-accelerometer torquing coil and drives the floated pendulous element until the X-accelerometer pickoff error signal is zero.

Exercises (645):

1. In figure 6-5, what determines the polarity of the DC signal out of demodulator Q4?

2. When are the accelerometers repositioned?

3. What are the inputs to the demodulator? Refer to figure 6-5.

4. Where is the power amplified output signal applied?

6-5. Gyro Torquing Loops

Four gyro torquing loops are used by the system. These loops generate the gyro torquing signals which position the platform stable element leveled with respect to local vertical and oriented with respect to true north. The four gyro torquing loops are X-axis, Y-axis, Z1-axis, and Z2-axis torquing loops. An illustration will be used in our discussion of each loop.

646. Using a detailed block diagram, cite operational characteristics of the X-axis and Y-axis gyro torquing loops.

X-Axis Torquing Loop. The inputs to DC amplifier assembly 3A10 (see upper left center of foldout 14) are the sensed output of the Y-accelerometer, the Y-accelerometer bias, and the capacitance tachometer 3A24S3. The DC amplifier assembly 3A10 is biased by the platform Y-accelerometer bias voltage to compensate for inherent error of the Y-accelerometer.

During ALIGN, the output of assembly 3A10 is summed with the X-axis gyro bias voltage and applied to the X-torquing coil of the upper gyro XZ2. The output to the X-torquing coil precesses the upper gyro XZ2 until the sum of the Y-accelerometer signal and the Y-accelerometer bias voltage is zero. During the NAV mode, the output of assembly 3A10 is summed with the output of resistor 3A24R2A and applied to amplifier 3A12A. The output 3A12A is used as the input to 3A12B. The output of 3A12B is summed with the X-axis gyro bias voltage and applied to the X-torquing coil of upper gyro XZ2. The input to the X-torquing coil precesses upper gyro XZ2 until the sum of the Y-accelerometer signal and the Y-accelerometer bias voltage is zero.

During ALIGN, relays A26K7, A27K3, and 3A24A4K3 are energized. In the energized state, relay A26K7 changes the amount of Y-accelerometer bias voltage applied to assembly 3A10. In the energized state, relay A27K3 applies the output of DC amplifier assembly 3A10 to the X-torquing coil of upper gyro XZ2. In the energized state, relay A27K5 shorts out capacitor A27C4, allowing DC amplifier assembly 3A10 to operate as a high-gain amplifier. During Af, relay K4 is energized. In the energized state, relay K4 removes the short from RSF10 (in the platform), changing the input to assembly 3A10. During ALIGN and

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NAV, relay K1 is energized and removes the feedback circuit of DC amplifier assembly 3A10.

Y-Axis Torquing Loop. The inputs to DC amplifier assembly 3A4 (see upper left center of foldout 15) are sensed outputs of the X-accelerometer, X-accelerometer bias, barometric altitude correction, and capacitance tachometer 3A2S2. The DC amplifier assembly 3A4 is biased by the X-accelerometer bias voltage to compensate for inherent error of the X-accelerometer.

During ALIGN, the output of assembly 3A4 is applied to assembly 3A17. The output from the wiper arm of resistor 3A24R13B is applied through assembly 3A16, to assembly 3A17, where it is summed with the output from assembly 3A4 and the Y-axis gyro bias voltage. The output of assembly 3A17 is applied to the Y-torquing coil of the lower gyro YZ1 until the sum of the X-accelerometer signal and the X-accelerometer bias voltage is zero.

During the NAV mode, the output of assembly 3A4 is summed with the output of resistor 3A24R1A and applied to amplifier 3A6A. The output of 3A6A is routed as feedback to amplifier 3A6B. The output of 3A6B is summed with the output of 3A6A and the Y-axis gyro bias voltage at the input assembly 3A17. The output of assembly 3A17 is applied to the Y-torquing coil of the lower gyro YZ1 until the sum of the X-accelerometer signal and the X-accelerometer bias voltage is zero.

During ALIGN, relays A26K2, 3K34, and A24A4K3 are energized. In the energized state, relay 3A26K2 shorts out capacitor A26C2, allowing DC amplifier assembly 3A4 to operate as a high-gain amplifier. When energized, relay 3K34 applies ground to pin 13 of connector XA17, removing 3A6 from the circuit. Energized, relay A24A4K3 removes the capacitance tachometer feedback input to assembly 3A4. In Af, relays 3A27K3 and 3A28K8 are energized. Energized, relay 3A27K3 applies the output of assembly 3A4 to assembly 3A17. Energized, relay 3A28K8 applies the output of assembly 3A4, the output of 3A16, and the Y-axis gyro bias voltage to the Y-torquing coil of lower gyro YZ1. In ALIGN and NAV, relay K1 is energized and removes the feedback circuit from DC amplifier 3A4.

Exercises (646):

1. In foldout 14, what is the platform Y-accelerometer bias voltage used for?
2. In foldout 14, when is there an input to the X-torquing coil?
3. In foldout 14, what is the function of relay 3A26K7?
4. In foldout 15, during ALIGN, what is the input to the Y-torquing coil of the lower gyro YZ1 when the sum of the Ax signal and the X-accelerometer bias voltage is zero?
5. In foldout 15, what is the function of K1?

647. Given a detailed block diagram, explain the operation of the Z-axis gyro torquing loops by mode.

Z1 Torquing Loop (Gyrocompass Align). During the gyrocompass phase, the Y-acceleration is summed with the Y-accelerometer bias at the input of DC amplifier 3A10 (see upper center of foldout 16). The output of the DC amplifier is the -Y-axis acceleration signal (-Ay). The -Ay is applied to secant potentiometer R18C in integrator shaft assembly 3A24. The movable contact of potentiometer R18C is positioned by the latitude shaft of assembly 3A24. The output of R18C, Aysecϕ, is applied through the energized contacts of relay A26K7 and the oven assembly to DC amplifier assembly 3A5. The output of the DC amplifier is applied through the energized contacts of relay A28K11 to the summing point at the input of summing amplifier assembly 3A18. At this point, the Aysecϕ signal is summed with earth rate, transport velocity, and Z-axis gyro bias. The sum signal is amplified and applied as the Z-axis torquing current through parallel resistors 3A22A2R9 and A28R78 to the lower gyro Z1 torquer coil. During gyrocompass, the gain of summing amplifier assembly 3A18 is greatly increased by the addition of parallel feedback resistor A28R76 through the energized contacts of relay K16.

The Ay sec ϕ signal from DC amplifier assembly 3A5 is also applied through the closed contacts of relay A26K10 to assembly 3A11.

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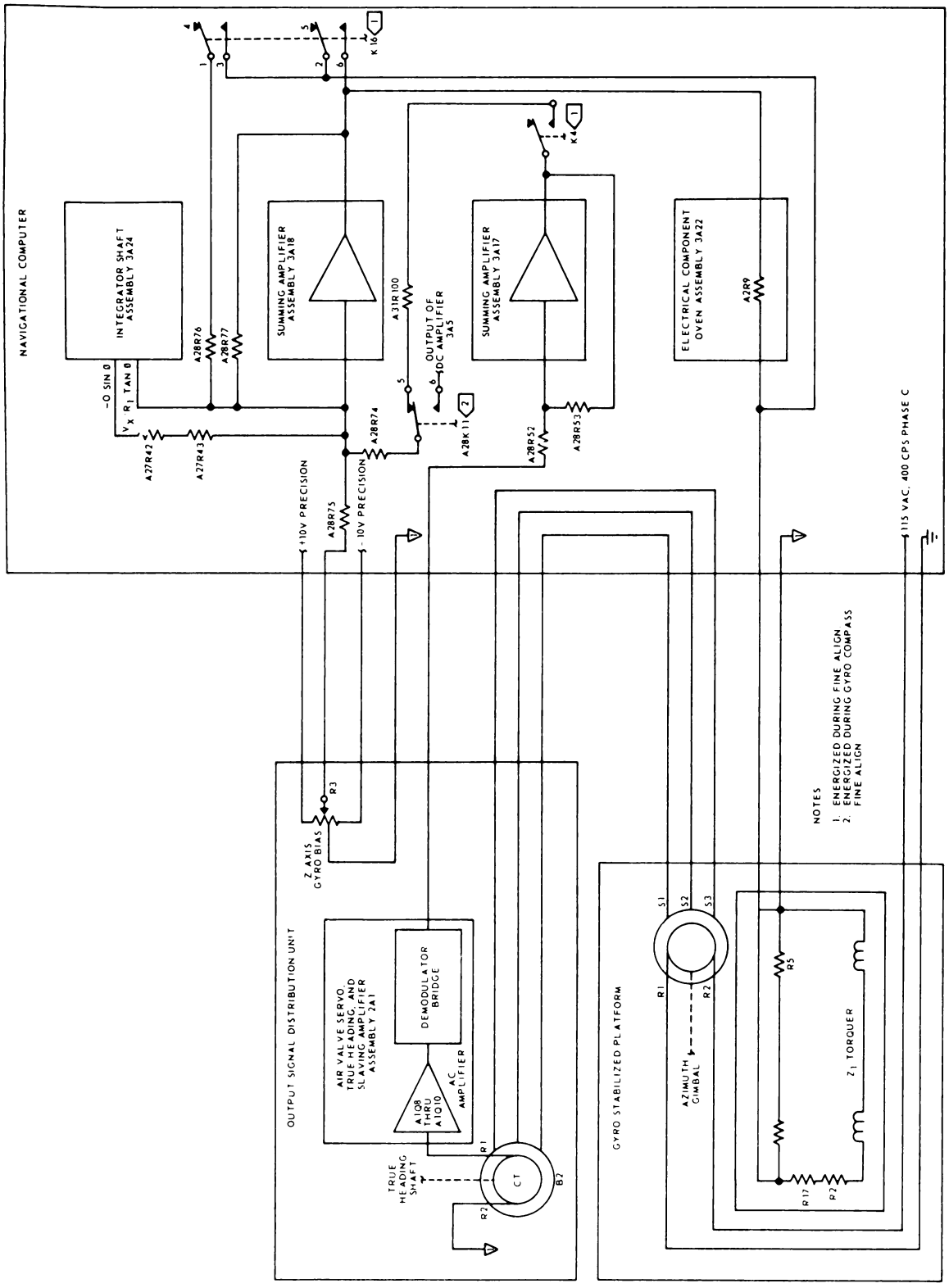

Figure 6-6. Z1 torquing loop (navigate).

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The output of this DC amplifier is applied to the level detector circuit in level detector and time delays assembly 3A14. When the Ay secϕ signal falls between +10 VDC and -10 VDC, the level detector circuit energizes relay K21. Relay K21 applies +28-VDC to the level 50-second time delay circuit in assembly 3A14. At the end of 50 seconds, provided the Ay secϕ signal level remains between +10 VDC and -10VDC, relay A28K29 is energized. Relay A28K29 applies +28 VDC to the flasher circuit in go/no-go, pitch angle detector, and flash assembly 3A8. The output of the flasher circuit alternately energizes and deenergizes relay K30, causing the ALIGN indicator on the control unit to flash, indicating INS alignment is complete.

Z1 Torquing Loop (Navigate). The function of this torquing loop is to provide a current proportional to the combination of earth rate, transport velocity, and Z-axis gyro bias (fig. 6-6). Earth rate and transport velocity are computed in the latitude integrator, combined with Z-axis gyro bias, and applied to summing amplifier 3A18. The output of the summing amplifier is the Z1-axis torquing current and is applied through the component oven to the lower gyro Z1 torquer coil. This signal drives lower gyro Z1, keeping the Z1-axis aligned to the desired reference.

Z2 Torquing Loop. The Z2 torquing loop provides current to the upper gyro Z2 torquing coil to maintain the Z2 portion of the Z-axis

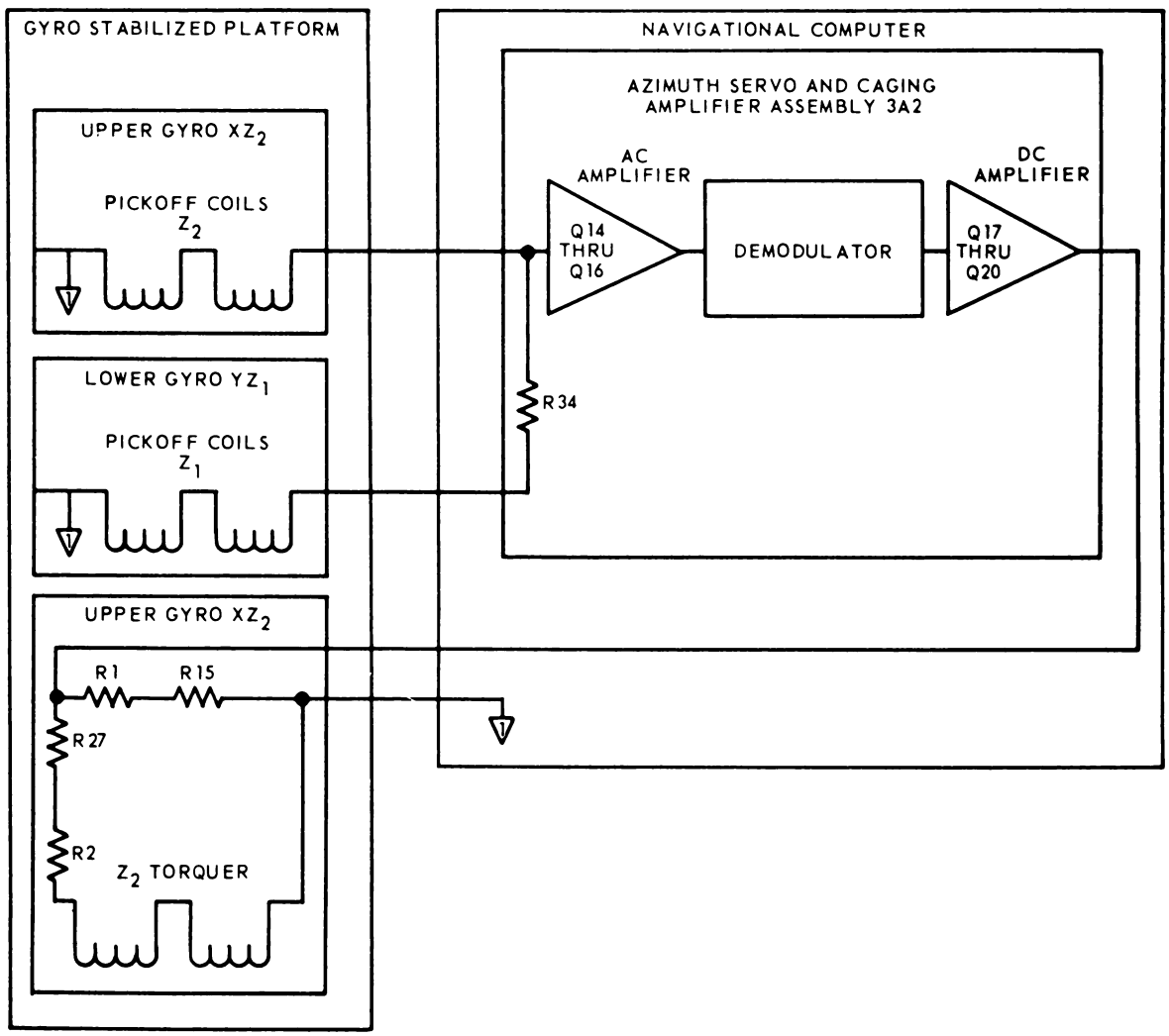

Figure 6-7. Z2 torquing loop.

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parallel to the Z1 portion (see fig. 6-7). There are no computed functions in the Z2 torquing loop. The current applied to the torquer coil is developed in the caging amplifier portion of azimuth servo and caging amplifier assembly 3A2. The input to the caging amplifier is the sum of both Z1 and Z2 pickoff coil outputs.

Exercises (647):

1. In foldout 16, what signals are summed together and used to torque the Z1 torquer?

2. In foldout 16, when does relay K21 apply +28 VDC to the level 50-second time delay circuit?

3. What is the function of the Z1 torquing loop during the NAV mode?

4. In figure 6-7, what is the input to the AC amplifier in assembly 3A2?

5. In figure 6-6, what inputs are applied to assembly 3A18 during navigate?

6. Refer to foldout 16. How is the gain of amplifier assembly 3A18 increased during gyrocompass?

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CHAPTER 7

Assembly Circuit Analysis

IN THIS CHAPTER, we present a circuit analysis of the assemblies used throughout the INS. In presenting the circuit analysis, we break the INS into major sections. These sections are the environmental control circuits, power assemblies, time delay, detector and flasher circuits, gimbal positioning servoamplifiers, and velocity and position integrating circuits. Each of these sections is composed of one or more transistorized printed-circuit boards. In studying this chapter, we recommend that you turn to Chapter 6 and briefly review the assembly being discussed. In this way, you can tell at a glance the input(s), output(s), and function of the assembly. The review will also remind you of how the assembly fits into the system.

7-1 Environmental Control Circuits

For the INS to attain maximum navigational accuracy, its operating temperature must be maintained within a close tolerance. Assemblies 3A23, 3A22, and the air valve amplifier on assembly 2A1 maintain the proper operating temperature of the INS. In this section, we present a circuit analysis of these assemblies. Refer to foldout 5 for a block diagram illustration of the temperature control circuits.

648. Trace the gyro temperature control and detector assembly and cite operational characteristics.

Gyro Temperature Control and Detector Assembly 3A23. The functions of the gyro temperature control and detector assembly are:

- To supply controlled heater power necessary to bring the gyros, accelerometers, and platform ambient heaters to operating temperature.
- To maintain the operating temperatures with a high degree of accuracy.
- To initiate a 50-second time delay when the gyros are at the proper operating temperature.

The gyro temperature control and detector assembly contains three temperature-sensing amplifiers, a power supply, a detector circuit, and a relaxation oscillator. Identify these circuits in foldout 17 and study them closely as we discuss each one.

The ambient thermistor output and the 8-Hz relaxation oscillator output control this assembly. The ambient thermistor output, a DC analog of temperature, controls bias on A1Q3, A1Q9, and A1Q15. This bias determines the amount of heating during each duty cycle provided by the relaxation oscillator. The output of the relaxation oscillator (8 Hz) is applied to the base of A1Q3, A1Q9, and A1Q15. This sawtooth voltage sets up the duty cycle of these transistors, thus controlling the time they can conduct. Note resistors A1R68 and A1R69 in the emitter-collector circuit of A1Q9 and A1Q15 respectively. These resistors limit the power available to the heaters at 70 percent. There is no resistor in the emitter-collector circuit of A1Q3; therefore, 100 percent of the available power can be applied to the ambient heaters.

Ambient temperature-sensing amplifier. The output of the ambient temperature control differential amplifier is controlled by a thermistor located inside the platform shell. Deviations from 125° F. in the ambient atmospheric temperature inside the platform housing cause the thermistor resistance to change. The change in resistance produces an error signal that is applied to the differential amplifier. The amplifier then controls the period of current flow through the heaters to correct the error signal. The ambient temperature-sensing circuits (A1Q1 through A1Q6) are located on the upper left part of foldout 17.

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Bias on A1Q1A is determined by current flow from ground through two thermistors (in the platform) and resistor A1R1 to the positive side of the power supply. The two thermistors are connected externally to the circuit at the junction of A1R1 and A1R2. Resistor A1R7 controls the bias on the base of transistor A1Q1B. You adjust this resistor so that, when the platform ambient temperature is at the correct operating level, the differential amplifier is balanced. Capacitor A1C1 keeps the base of A1Q1A referenced to AC ground. Resistor A1R3 provides negative feedback to stabilize the amplifier.

When the temperature of the platform rises, the potential at the junction of A1R1 and A1R2 decreases because of the decrease in thermistor resistance. This reduces the forward bias on A1Q1A, and the potential at the base of A1Q1A decreases. This increases the forward bias of A1Q1B and causes the potential at its collector to decrease. The negative-going potential at the collector increases the forward bias on the base of A1Q2. Additional current through A1Q2 causes the collector of A1Q2 and the emitter of A1Q3 to go positive. An increase in the positive potential at the emitter of A1Q3 requires the sawtooth voltage at its base to reach a more positive potential before it is forward biased. When A1Q3 conducts, its collector voltage causes A1Q4 to be forward biased. If A1Q4 is not conducting, A1Q5 is forward biased by a DC voltage created by diodes A1CR2 and A1CR3. The DC voltage biases A1Q5 by causing current to flow from ground through resistors A1R13, A1R15, and A1R16, and diodes A1CR2 and A1CR3 to the secondary winding of the transformer T6. (T6 is mounted on assembly A3). The resistance in this path is so large that the current in the primary winding of transformer A1T1 does not induce sufficient voltage in the secondary winding to forward bias diodes CR1 and CR2. The collector of A1Q5 is at ground potential when it is forward biased to saturation. This causes A1Q6 to be back biased and nonconducting. Transistor A1Q5 synchronizes the conduction of diodes CR1 and CR2 with the start of each duty cycle (the period when A1Q4 conducts during each 8Hz sawtooth signal). If A1Q4 starts to conduct while the ϕB of the input power is other than zero, the collector of A1Q5 is at ground potential and the current through A1Q4 goes to ground through A1Q5, instead of through A1R14, and does not forward bias A1Q6.

When the ϕB of the input power crosses zero potential, A1Q5 is back biased and current starts to flow through A1R14. This causes A1Q6 to be forward biased. Transistor A1Q6 saturates and the ground at its collector maintains A1Q5 back biased at cutoff until A1Q4 becomes back biased because of the collapse of the sawtooth voltage. With A1Q6 saturated, current through the primary winding of A1T1 induces a voltage in the secondary windings sufficient to forward bias diodes CR1 or CR2 on each half-cycle of the input power.

The ϕA input power is applied to the anode of diode CR1 and the cathode of diode CR2. The difference in potential between ϕA and ϕB of the input power is applied across the ambient heater through diodes CR1 and CR2. During the duty cycle, the gate voltage is always sufficient to cause either diode CR1 or CR2 to conduct at the crossover point of the ϕA and ϕB input power. This is illustrated on the right-hand side of foldout 17. Diodes CR1 and CR2 are switched on and off when the power to the gyro heaters is maximum. The noise generated by switching diodes CR1 and CR2 is filtered by the two inductors (mounted on assembly A3) and capacitor C9.

Operation of the ambient temperature-sensing amplifier for low temperatures is essentially the same as for high temperature. The thermistor resistance increases and the potential at the junction of A1R1 and A1R2 increases, increasing the forward bias on A1Q1A. Additional current through A1R4 decreases the forward bias of A1Q1B, and the collector goes more positive. The positive going voltage at the collector of A1Q1 decreases the forward bias on A1Q2. As a result, the positive potential at the collector of A1Q2 decreases. The decrease in positive potential at the collector of A1Q2 is applied to the emitter of A1Q3. Transistor A1Q3 becomes forward biased at a lower point on the rising portion of the sawtooth voltage. Once A1Q3 conducts, the operation during the remainder of the cycle is identical to that described for the high-temperature condition except that current flows for a greater portion of the duty cycle. When the proper temperature is attained, thermostat S3 opens, thereby opening the ambient heater circuit.

Upper gyro temperature-sensing amplifier. The upper gyro temperature-sensing amplifier operates in the same manner as the ambient temperature-sensing amplifier. Note that the upper and lower gyro temperature circuits have an additional resistor (A1R68 and A1R69 respectively). The operating temperature of the upper gyro differs from the ambient operating temperature; therefore, the added resistance is necessary to balance the amplifier when the operating temperature is reached. Resistor A1R68 maintains a positive voltage on the emitter of A1Q9. As a result, the sawtooth

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voltage on the base of A1Q9 must reach at least 30 percent of its peak value before A1Q9 can conduct. Therefore, the duty cycle cannot exceed 70 percent of the possible conduction time, and not more than 70 percent of available power can reach the upper gyro heater.

Lower gyro temperature-sensing amplifier. Operation of the lower gyro temperature-sensing amplifier is identical to that of the upper gyro temperature-sensing amplifier. Resistor A1R69 maintains a positive voltage on the emitter of A1Q15 to insure that not more than 70 percent of the available power reaches the lower gyro heater.

Gyro temperature detector. When the upper and lower gyros reach the correct operating temperature, the gyro temperature detector initiates the 50-second time delay. The potential difference between ϕA and ϕB of the 400-Hz power applied to the upper and lower gyro heaters is also applied to the detector circuit. The heater voltage dropped across A2R56 drives the primary winding of A2T4, and the voltage dropped across A2R57 drives the primary winding of A2T5. When ϕA is more positive than ϕB, the voltage induced in the secondary winding of A2T4 forward biases A2CR14, and the voltage induced in the secondary winding of A2T5 forward biases A2CR15. During the time that A2CR14 and A2CR15 are forward biased, capacitor A2C12 starts to charge to the negative voltage induced in the secondary windings of the transformers. The charging current back biases the base of A2Q22. When ϕB is more positive than ϕA, the voltage induced in the secondary windings back biases A2CR14 and A2CR15. During the time that the diodes are back biased, A2C12 starts to charge to the *positive* supply voltage. When A2Q22 is back biased, A2Q23 is forward biased. The voltage drop across A2R65 is sufficient to break down zener diode A2CR17 and forward bias A2Q25. Transistor A2Q25 saturates and provides a ground for the gyro heat signal, causing the heat indicator on the unit control to illuminate.

As the temperature of the upper and lower gyros approaches the correct operating temperature, diodes A2CR14 and A2CR15 are back biased more during each cycle of the sawtooth voltage. As a result, the charge on A2C12 changes from negative to positive. The positive charge on A2C12 forward biases A2Q22, and it conducts. When the transistor is forward biased, the voltage drop across A2R63 back biases A2Q23. The voltage drop across A2R65 is no longer sufficient to break down A2CR17, and A2Q25 becomes back biased, removing the ground from the gyro heat signal, causing the heat light on the INS control to extinguish. With A2Q23 back biased, zener diode A2CR16 breaks down and forward biases A2Q24. When A2Q24 conducts, A2Q26 saturates and the +28-VDC fine align signal is applied through A2Q26 to initiate the 50-second time delay on assembly 3A8.

Relaxation oscillator. Transistor A1Q21 and associated components comprise a sawtooth generator. At the beginning of an operating cycle, the emitter of A1Q21 is reverse biased and is nonconducting. As capacitor A1C8 charges through resistor A1R53, the emitter voltage rises exponentially toward the supply voltage. When the voltage across A1C8 reaches the voltage of the base of A1Q21, the emitter becomes forward biased and the resistance between the emitter and base drops to a low value. Capacitor A1C8 discharges rapidly through the emitter and diode A1CR13 to ground. When the voltage across capacitor A1C8 reaches a low value, the emitter becomes back biased again and causes the transistor to cease conduction. Capacitor A1C8 begins to charge again to repeat the cycle. The sawtooth rate is 8 Hz. This sawtooth is the bias on the bases of A1Q3, A1Q9, and A1Q15, and thus controls their conducting time.

Power supply. This is the power supply for the gyro temperature control and detector. Don't confuse it with the major power supply assembly (3A25) discussed later in this chapter. In the energized state, relay A1K1 applies ϕB, 115-VAC, 400-Hz power from its contact 11 to the primary winding of the transformer mounted on assembly A3. The output of the transformer is rectified by A1CR10 and A1CR11, filtered by A1C7 and regulated by A1Q19, A1Q20, and A1CR12 at approximately +23 VDC. When the rectified output rises, more current flows through A1R51, increasing the forward bias on A1Q20. This increases the collector-to-emitter resistance of A1Q19, which is in parallel with A1R50. The increased total resistance of A1Q19 and A1R50 causes a larger voltage drop and thus maintains the output voltage at +23 VDC. Zener diode A1CR12 maintains a constant potential between the emitter of A1Q19 and the base of A1Q20. When the rectified voltage starts to decrease, less current flows through A1R51, lowering the forward bias on A1Q20 and reducing the current through A1Q20. Reduced conduction through the transistor increases the forward bias on A1Q19 and reduces its collector-to-emitter resistance. (Note that this resistance is in parallel with A1R50.) As a result, the total resistance of A1R50 and A1Q19 is reduced, decreasing their voltage drop and thus maintaining the +23-VDC output at a constant amplitude.

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Exercises (648):

1. What is the purpose of A1R7 in foldout 17?

2. What is the function of A1C1 in foldout 17?

3. What effect does a negative going potential at the collector of A1Q1B (foldout 17) have on the forward bias on the base of A1Q2?

4. What is the potential of the collector of A1Q5 in foldout 17 when this transistor is forward biased to saturation?

5. In foldout 17, what effect does current flow through A1R14 have on transistor A1Q6?

6. Refer to foldout 17. When are CR1 and CR2 switched on and off?

7. In foldout 17, when thermistor resistance increases and the potential at the junction of A1R1 and A1R2 increases, what happens to the forward bias on A1Q1A?

8. What is the maximum percentage of available power that can reach the upper gyro heaters?

9. What initiates the 50-second time delay?

10. Refer to foldout 17. What happens to A2C12 the instant A2CR14 and A2CR15 become back biased?

11. When is transistor A2Q25 forward biased?

12. Refer to foldout 17. What back biases the base of transistor A2Q22?

13. Refer to foldout 17. What type voltage is used as bias on the bases of A1Q3, A1Q9, and A1Q15?

14. What is the function of A1CR10 and A1CR11 shown in foldout 17?

15. What effect does a decrease in current flow through A1R51 (foldout 17) have on the forward bias on A1Q20?

16. What controls the amount of heating during each duty cycle provided by the 8 Hz relaxation oscillator?

17. Refer to foldout 17. During what INS modes of operation is relay A1K1 energized?

18. What is the function of zener diode A1CR12?

19. Refer to foldout 17. What signal is required to energize relay A1K1?

20. The voltage drop across what component drives the primary winding of A2T4?

21. Refer to foldout 17. As upper and lower gyros approach the correct operating temperature what happens to the charge on A2C12?

22. Why do the upper and lower gyro temperature circuits each have an additional resistor not found in the ambient temperature-sensing amplifier circuit?

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23. Refer to foldout 17. When is the value of resistors A1R68 and A1R69 determined?

24. What are the 3 basic functions of the 3A23 gyro temperature control and detector assembly?

649. Specify the operational status of environmental circuit components.

Electrical Component Oven Assembly 3A22. The component oven provides environmental temperature control for precision resistors, capacitors, potentiometers, inductors, and a zener diode. Refer to figure 7-1 for a schematic diagram of assembly 3A22. The environmental circuits in this assembly are located at the very bottom of the schematic. The remaining components are part of circuits on other assemblies and will be explained later.

The environmental circuits comprise control thermostat S1, booster thermostat S2, and a 10- and 20-watt heating element. When the INS is in the STBY, ALIGN, or NAV mode, the control thermostat is closed and 115-VAC, 400-Hz, ϕB power is applied to the 20-watt heating element. The booster thermostat controls the 10-watt heating element in series with the control thermostat so that both thermostats must be closed to energize the 10-watt element. The temperature control oven heaters operate independently and are not affected by the platform heating circuits discussed earlier.

Exercises (649):

1. When the INS is in STBY, ALIGN, or NAV, what is the state of S1?

2. What is the condition of thermostats S1 and S2 in figure 7-1 when the 10-watt heater is energized?

650. Trace the air valve amplifier on a schematic diagram and cite the purpose of specified circuit components.

Air Valve Amplifier. The air valve amplifier promotes the drive signal for the air valve servomotor. A schematic of the air valve amplifier on assembly 2A1 is in the center of foldout 18. The remainder of the circuits on this assembly are explained later in this text.

The amplifier receives two inputs: the air valve thermistor bridge and servo potentiometer output; its output is proportional to the difference between the two inputs. The two input voltages are summed at the junction of R24 and R26 and applied across R27 to the emitter of Q7. The voltage at the emitter of Q7 is modulated at 400 Hz by the voltage applied to its base, and coupled through C16 to the base of Q8. The signal is amplified in Q8 and direct-coupled to Q9 which, with Q10 and T3, forms a phase inverter for compound-connected, push-pull output transistors Q11, Q12, Q13, and Q14. The small DC voltage developed across CR7 and CR8 is used as bias for Q11 and Q12. Transformer T3 is connected so that half the primary winding is the collector load for Q9 and the other half is the collector load for Q10. A positive change in voltage at the base of Q9 causes an increase in current flow through its half of the T3 primary. The increased current causes a positive change in voltage at the junction of R32 and R33 that is applied to the emitter of Q10. The positive change at the emitter of Q10 reduces the current through the transistor and its half of T3 primary. A negative change in voltage has the reverse effect on the currents in the primary of T3. These changes in current in the primary of T3 induce voltages in the secondary that drive compound-connected, push-pull output transistors Q11 through Q14. The output of Q13 and Q14 drives the air valve servomotor that circulates cooling air about the inner shell of the platform.

Exercises (650):

1. Refer to foldout 18. Where do we obtain the base bias voltage for Q11 and Q12?

2. Refer to foldout 18. What is the purpose of Q9, Q10, and T3?

7-2. Power Assemblies

In this section, we present the power-interrupt circuits, power supplies, and the

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regulator circuits. Because of the limited number of circuits in the OSDU power supply and the thorough coverage in Chapter 6, we do not analyze it in this chapter.

651. Trace the power-interrupt circuits on a specified schematic diagram and cite the purpose of specified components.

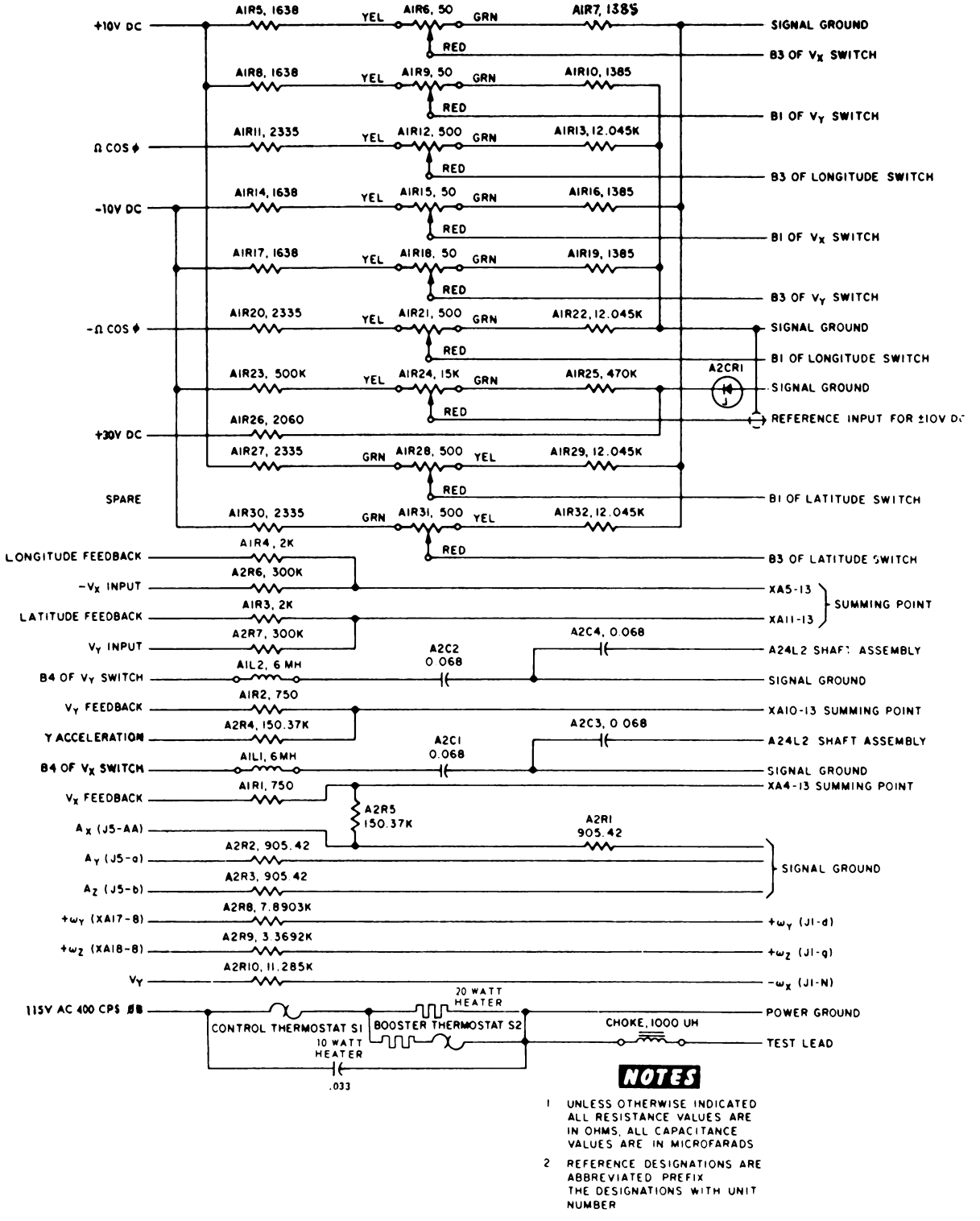

Figure 7-1. Electrical component oven assembly 3A22.

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Power-Interrupt Circuits. The function of the power-interrupt circuit is to insure that relays K1 and A4K1 (located on the integrator shaft assembly) remain deenergized for approximately 250 milliseconds after INS power is turned on. The power-interrupt circuit is on the uppermost part of foldout 19. Refer to this foldout as we discuss this circuit.

When the INS is in either the NAV or ALIGN modes of operation, +28 VDC is applied across A1R5 and through A1R2 to the base of Q1. During the 250-millisecond time delay, the deenergized contacts of relay K1 connect a feedback resistor across DC amplifiers 3A4 (foldout 10) and 3A10 (foldout 11), reducing their gain. The deenergized contacts of relay A4K1 open the ground contacts of motors B3 and B4, preventing the Vx and Vy shafts from being driven.

The voltage at the junction of A1R1 and A1R5 is about +9.4 volts DC. The RC network, consisting of A1R2 in parallel with the back resistance of A1CR1 and A1C1, requires approximately 250 milliseconds to charge A1C1 sufficiently to overcome the breakdown voltage (+6.3 VDC) of zener diode CR1, causing Q1 through Q3 to conduct. Transistor Q3 is driven to saturation, energizing relays K1 and A4K1, which are connected to the collector of Q3. The energized contacts of K1 disconnect the resistive feedback circuit and increase the gain of DC amplifiers 3A4 (foldout 10) and 3A10 (foldout 11). The energized contacts of A4K1 apply a return to the X and Y velocity shaft servomotors, which apply torque to the velocity integrator shafts. Diode A1CR1 provides a rapid discharge path for A1C1 when +28 VDC is removed from the circuit.

Exercises (651):

1. What circuit insures that relays K1 and A4K1 (foldouts 10 and 11) remain energized for approximately 250 milliseconds after power is turned on?

2. Refer to foldout 9. What components provide the 250 millisecond delay when power is turned on?

652. On a specified schematic diagram, trace the development of the regulated +30 VDC and -30 VDC, filtered and unfiltered +28 VDC, standby +28 VDC, 12.6 VAC, 6.3 VAC, and 5.8 VAC power supplies.

Power Supply Assembly 3A25. Power supply assembly 3A25 is shown in foldout 20. This assembly contains the INS power supply relays and power supplies discussed in the previous chapter. Operation of the relays and a circuit analysis of the power supplies are presented in this section. Here, we do not discuss the circuits (Q1 through Q6) located in the upper left corner of foldout 20. Instead we cover this section of the foldout after we show how the 4.5-kHz and 375-Hz drive signals are generated.

Power supply relays. Refer to foldout 20 and follow the schematic diagram as we discuss assembly 3A25. The function of relays A1K3 and A1K4 is to connect 115-VAC, 400-Hz, 3-phase power to the INS power supplies. These relays are energized when you set the unit control mode selector switch to either ALIGN or NAV. In either of these positions, ϕC power is applied through A1R5 to diode bridge A1CR4 (top center of foldout 20). Ground for A1CR4 is through pins 1 and 4 of A1K8. Diode bridge A1CR4 rectifies the ϕC voltage to provide the energizing current for A1K3 and A1K4. During the positive portion of the AC voltage, current flows from ground into A1CR4 on the bottom yellow lead and out of the blue lead through the coils of A1K3 and A1K4. From pin 7 of A1K3, the current goes out of the assembly through the primary power control circuits and back into assembly 3A25 to R1 (upper right of foldout 20). From R1, the current goes in to A1CR4 on the red lead and out on the yellow lead (top) through A1R5 and back to the power supply. During the negative portion of ϕC, current flows from the power supply through A1R5 into A1CR4 on the top yellow lead. From A1CR4, current flows on the blue lead through the coils of A1K3 and A1K4. From pin 7 of A1K3, current flows out of assembly 3A25 through the interlock circuits and back into the assembly to R1. From R1, current flows into A1CR4 on the red lead and out of A1CR4 on the bottom yellow lead, through the NC contacts of A1K8 to ground.

The function of A1K7 is to energize A1K8 if the voltage from the +30-VDC, -30-VDC, +28-VDC filtered, or the +28-VDC unfiltered power supply does not stay within the set limits. The function of A1K8 is to deenergize the INS power supplies by causing A1K3 and A1K4 to deenergize. Relay A1K7 is energized as long as the voltages mentioned above stay

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within the set limits. When any one of the voltages goes above or below the set limit, the ground is removed from pin 8 of A1K7 by the power supply disable circuit, causing A1K7 to deenergize. When A1K7 is deenergized and A1K3 and A1K4 are energized, ϕB voltage is applied to the coil of A1K8.

The current path is from ground through contacts 1 and 4 of A1K7 to pin 8 of A1K8. From pin 8, the current goes through the coil and out of pin 7 through A1R4, contacts 2 and 5 of A1K7, A1CR3, A1R13, contacts 2 and 5 of A1K8, contacts 1 and 3 of A1K4, and off the assembly on the lower left part of foldout 20 to the power source. For about 250 milliseconds after A1K7 is deenergized, A1K8 does not energize. It takes 250 milliseconds for the voltage across A1C16 and A1C17 to build up enough to energize A1K8. Note that this is a DC path, since A1CR3 is in series. Capacitors A1C16 and A1C17 are in parallel with the coil of A1K8 and the voltage builds up at an exponential rate. When the charge on these capacitors becomes sufficiently large, current flows through the coil of A1K8. When A1K8 is energized, ground is removed from A1CR4 and, as a result, A1K3 and A1K4 are deenergized, deenergizing the INS power supplies.

The +30-VDC regulated power supply. The 115-VAC, 400-Hz, 3-phase voltage to this power supply comes into the assembly on the lower left corner in foldout 20. The 3-phase voltage is applied through NO contacts 3 and 1 of A1K3 and NO contacts 2 and 6 and 1 and 3 of A1K4 to FL1. From FL1, the 3-phase voltage is applied to the Y-connected primary winding of T6. The nine windings on the secondary of T6 are delta-connected in three sections. Capacitors A2C2, A2C3, A2C5, A2C6, A2C8, and A2C9 are hash suppressors. Diodes A2CR1 through A2CR6 form a 3-phase full-wave rectifier for the output at terminals 8 through 10 of T6. The rectified output is filtered by inductor A1L1-A and capacitors A2C4 and C1 to produce a +45-VDC unregulated voltage. The +45-VDC output is regulated to +30 VDC on regulator electronics and power supply assembly 3A21. (Assembly 3A21 is explained later.) The +30-VDC output is returned to assembly 3A25 (lower left corner of foldout 20) so the collector-to-emitter resistance of Q7, in series with the paralleled resistance of A1R7 and A1R8, is varied. The +30-VDC regulator control signal insures that the +30-VDC regulated output (lower left of foldout 20 is maintained at +30 VDC.

The -30-VDC regulated power supply. Input to this power supply is also from T6. Diodes A2CR7 through A2CR12 form a 3-phase, full-wave rectifier whose output is filtered by inductor A1L1-B and capacitors A2C7 and C2. The voltage at the junction of C2 and A1L1-B is unregulated +15 VDC with respect to ground. The junction of C2 and C7 is -30 VDC with respect to ground. The positive side of C2 is connected to ground through Q8, A1R9, and A1R10. The -30-VDC regulator control signal varies the collector-to-emitter resistance of Q8 to insure that the -30-VDC regulated output (lower right of foldout 20) is maintained at -30 VDC.

The +28-VDC filtered power supply. The input to this power supply is from T6, which is connected to 115-VAC 400-Hz, 3-phase power. Diodes CR3 through CR8 form a 3-phase full-wave rectifier for T6 outputs. Capacitors A1C12 and C3 and inductor A1L2 filter the rectified output. The resulting filtered voltage output on the right side of A1L2 is the +28-VDC power for the system. Current drain on this power supply is limited to 5 amperes by fuse A1F5.

The +28-VDC unfiltered power supply. The function of this power supply is to provide collector voltage to transistors in the final stages of the various INS servoamplifiers. The power applied to the primary of stepdown transformer T4 is 115 VAC, 400 Hz, ϕA and ϕB. The stepdown secondary voltage of T4 is applied to CR1 and CR2, a full-wave rectifier circuit, and provides the +28-VDC unfiltered voltage. Current drain on this power supply is limited to 5 amperes by fuse A1F4.

Standby +28-VDC power supply. The function of this power supply is to energize K22 when the unit control mode selector switch is set to STBY. Recall from Chapter 6 that K22 is located on the computer main chassis and provides ground for the primary control relays. Diodes A1CR5 through A1CR7 form a half-wave rectifier for the 115-VAC, 400-Hz, 3-phase power. The rectified output is reduced by R2 and R3 to +28 VDC.

The 12.6-VAC 400-Hz power supply. The function of this power supply is to provide a modulating signal for DC levels in azimuth servo and caging amplifier assembly 3A2, inner roll and pitch servoamplifier assembly 3A3, and outer roll servoamplifier assembly 3A1. The 12.6-VAC 400-Hz power is generated by stepdown transformer T4. The primary winding of T4 is driven by 115-VAC, 400-Hz, ϕA and ϕB voltage.

The 6.3-VAC 400-Hz power supply. The function of this power supply is to provide a reference voltage for the mechanical vibrators. The 6.3-VAC power is generated by stepdown

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transformer T5. Primary power to T5 is driven by 115-VAC, 400-Hz, ϕA and ϕC voltage.

The 5.8-VAC 400-Hz power supply. The function of this power supply is to provide antibacklash voltage to the servomotors. The voltage provides opposition to the backlash of the gear trains in the servoloops. The 5.8-VAC antibacklash voltage is supplied by stepdown transformer T4.

Exercises (652):

1. Refer to foldout 20. What component provides ground for A1CR4?

2. Describe the chain of events (foldout 20) that occur if either the +30-VDC, -30-VDC, +28-VDC filtered, or the +28-VDC unfiltered exceeds the limits set in assembly 3A21.

3. Refer to foldout 20. What components are used to filter the +45-VDC unregulated output?

4. What components (foldout 20) do we use to rectify the output of T6 to produce the -30 VDC?

5. What use do we make of the output of the +28-VDC unfiltered power supply (foldout 20)?

6. What are the functions of R2 and R3 (foldout 20) in the standby +28-VDC power supply?

7. Refer to foldout 20. What use do we make of the output of the 12.6-VAC 400-Hz power supply?

8. Refer to foldout 20. When will relays A1K3 and A1K4 be energized?

9. How is relay A1K7 deenergized if the +30-VDC or -30-VDC power supply has no output or an incorrect output?

10. If the +28-VDC-filtered or +28-VDC-unfiltered power supply is out of tolerance intermittently for periods of 200 milliseconds or less, what will happen and why?

11. What power supply voltages would be incorrect if transformer 3A25T4 shorted?

12. Refer to foldout 20. What is the amperage rating of the fuse protecting the +28-VDC-unfiltered power supply?

13. Diodes A1CR5 through A1CR7 perform what function?

14. Where is the +28-VDC-standby power supply output used?

653. Using a specified schematic diagram, trace the +30-VDC and -30-VDC regulators, the 4.5-kHz power supply, and the voltage monitoring circuit.

Regulator Electronics and 4.5-kHz Power Supply Assembly 3A21. This assembly contains a +30-VDC regulator, a -30-VDC regulator, a voltage monitoring circuit, and a 4.5-kHz precision reference voltage power supply. As we discuss each of these circuits individually, refer to foldout 21 to trace the signal.

The +30-VDC regulator. This regulator, operating in conjunction with regulator circuit Q7 (located in assembly 3A25), provides a +30-VDC ±15-volts precision source of power from the +45-VDC unregulated input voltage (discussed earlier). The +30-VDC regulator consists of three circuits: a temperature

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compensated differential amplifier, a variable impedance regulator circuit, and an overload diode for circuit protection.

The +45-VDC unregulated and the +30-VDC regulated inputs to this circuit (upper left of foldout 21) are supplied from assembly 3A25. Ordinarily, if either of these two voltages changes, the other voltage will change accordingly. The +30-VDC regulated input is dropped across voltage divider network R7, R8, and R9. Transistors Q3 and Q4 form a differential amplifier that is sensitive to any voltage variations at the base of Q4. Variable resistor R8 is adjusted so that the regulator circuit provides a +30-VDC ±.15-volt precision output from Q2.

Any variation in the +45-VDC unregulated and/or +30-VDC regulated inputs is sensed at the wiper arm of R8 and the base of Q4. If either of the voltages increases, the resulting higher positive potential at the base of Q4 increases forward bias. The increase in forward bias causes the current through Q4 to rise. The higher current through Q4 causes a larger voltage drop across R1, which lowers the potential at the base of Q1. Decreasing the forward bias on compound-connected transistors Q1 and Q3 increases the collector-to-emitter resistance of both transistors. The higher resistance of the two transistors increases their voltage drop, maintaining the +30-VDC ±.15-volt precision control voltage output (upper left of foldout 21) at a constant level. The control voltage is applied to the base of regulator transistor Q7 on assembly 3A25 (foldout 20). If either of the input voltages to the +30-VDC regulator decreases, then the opposite of the above explanation is applicable.

Changes in conduction of Q4, due to change in temperature, appear as output voltage changes to the regulator circuit. Changes in conduction of Q4 are compensated for by opposite changes in the conduction of Q3. The base bias of Q3 is fixed at +9.3 VDC by resistor R2 and diode CR1 (between the regulated output and power ground), so any change in its conduction is caused by a change in the emitter potential. The emitters of Q3 and Q4 have a common-emitter resistor, R5. Any variation in conduction of Q4 will vary the emitter potential across R5, compensating for any change in the operating temperature of the regulator.

The regulator circuit is protected from a short circuited overload by CR2. When an overload occurs, the decreased output voltage is sensed at the base of Q4. Transistor Q4 becomes back biased, close to cutoff, and the potential at the base of Q1 starts to rise to +45 VDC. When the base of Q1 becomes 6.7 volts positive with respect to the emitter of 3A25Q7 (foldout 20), CR2 breaks down and thus limits the bias on the emitter of 3A25Q7 to +6.7 VDC. This limits the maximum conduction level and prevents damage to Q1, Q2, and 3A25Q7. Additional protection is provided by R6, R8, and R9. This network provides positive bias to the Base of Q4 at all times, unless the power supply fails. This positive bias prevents Q4 from reaching cutoff, and thus limits the potential at the base of Q1.

The -30-VDC regulator. This regulator provides a -30-VDC source regulated to ±0.5 percent from a 45-VDC nongrounded rectifier output, and functions the same as the +30-VDC regulator. Inputs to the circuit are +15 VDC (unregulated) and -30 VDC. The regulated output voltage is negative instead of positive because the signal ground reference point and the regulated voltage output point are reversed from those in the +30-VDC regulator. The variable impedance consisting of the collector-to-emitter resistance of Q5, Q6, and 3A25Q8 is connected from one side of the power supply to ground. Any voltage from the rectifier in excess of -30 VDC is dropped across this variable impedance. Thus, the voltage from ground to the opposite side of the power supply is maintained at -30 VDC.

The 4.5-kHz power supply. The function of this power supply is to provide a 15-VAC 4.5-kHz precision reference voltage for gyro and accelerometer pickoff coil excitation and 115-VAC 4.5-kHz power for synchro excitation. The power supply also provides excitation for the 3-kHz tuning-fork generator, a 1.5-kHz input to gyro spin motor power supply assembly 3A20, and 4.5-kHz reference voltage for 4.5-kHz power amplifiers Q1 and Q2 in power supply assembly 3A25 (foldout 20). The power supply input is 3-kHz 300-millivolt square wave from the tuning fork generator. This square wave is applied to tuning fork oscillator transistors Q14 and Q15 to produce a 10-volt peak-to-peak signal at the collector of Q15. The voltage developed between the collector of Q14 and the collector of Q15 drives the tuning fork generator, which produces the input to the oscillator circuit.

Capacitor C10 couples the signal to the next stage. Capacitor C11 bypasses any high-frequency components of the signal. The signal waveshape is squared by CR13 limiting the signal from approximately ground to 10 volts. Transistor Q16 amplifies the square wave, producing a 25-volt peak-to-peak signal at its collector. This signal is coupled to CR14 through C14. A flip-flop consisting of Q17 and Q18 divides the 3-kHz signal to produce a 1.5-kHz square wave. The negative portion of

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the square wave is applied through CR14 and C16 or C17 at the base of flip-flop transistors Q17 and Q18. The collector potential of the "on" transistor is approximately ground, and the collector potential of the "off" transistor is approximately +22 VDC. If Q18 is the "on" transistor, the next negative portion of the square wave is applied through CR14 and C16 to the base of Q18. The negative pulse back biases the transistor. The potential at the junction of C17 and R50 rises quickly to approximately +22 VDC. Capacitor C17 couples the rising potential to the base of Q17, biasing it to saturation. The next negative portion of the square wave through CR14 turns Q17 "off" and Q18 "on".

Positive portions of the square wave are shunted to the junction of R41, R42, R45, and R50 and do not affect the operation of the flip-flop. The RC time constant represented by the coupling capacitor and resistor from the collector of one transistor to the base of the other determines the switching time of the flip-flop. Since the positive portion of the square wave does not affect the operation of the flip-flop, the state of Q18 is switched by each negative portion of the 3-kHz square wave. The signal developed at the collector of Q18 is a 1.5-kHz square wave, 22 volts peak to peak.

The 1.5-kHz signal is applied as an input to gyro spin motor power supply 3A20. (The 3A20 is explained later.) The 1.5-kHz signal is also direct-coupled from the collector of Q18 to the base of emitter-follower Q19. Transistor Q19 acts as a buffer between the flip-flop and the 4.5-kHz resonant tank circuit, consisting of C18L1. Since a parallel resonant circuit presents maximum impedance to signals at its resonant frequency and minimum impedance to all other frequencies, the 1.5-kHz signal and all harmonics except 4.5 kHz are not developed. The 4.5-kHz (third harmonic) signal is then amplified by Q20.

Transistor Q20 produces a signal with a constant amplitude from a varying input to its base. When the signal at the base of Q20 starts to go negative, the emitter potential is limited to the negative direction by CR15. The positive swing of the signal at the emitter is limited by the negative feedback developed across R54. The signal is filtered to remove everything but the 4.5-kHz sine wave by the 4.5-kHz tuned tank circuit formed by C19 and L2. Resistor R56 has a value between 75k ohms and 500k ohms. The exact value is determined during testing to control gain insuring that the output from the 4.5-kHz power transformer on assembly 3A25 is a 15-VAC sine wave.

Transistors Q21 and Q22 operate as a paraphase converter, producing two 4.5-kHz signals 180° out of phase, to drive push-pull driver transistors Q23 and Q24. Capacitor C20 decouples the AC signal developed across the primary winding of T1 from the +30-VDC power supply. Capacitor C21 and the primary winding of T1 form a 4.5-kHz parallel-resonant circuit to provide maximum signal transfer between the primary and secondary windings of T1.

The 4.5-kHz outputs of push-pull driver stage Q23-Q24 are applied to push-pull power amplifiers Q1 and Q2, located in assembly 3A25 (upper left of foldout 20). The input, controlled by feedback from terminal 6 of T1, insures that the voltage between terminals 6 and 8 of T1 is 15 volts. Resistors A1R1 and A1R2 are physically located in assembly 3A25 but electrically connected in the emitter circuits of the push-pull amplifier on assembly 3A21. The voltage developed across A1R1 and A1R2 alternately biases Q1 and Q2 on and off. The push-pull operation of Q1 and Q2 provides the primary winding current for T1. The voltage between terminals 4 and 5 of T1 is 115 VAC. A 4.5-kHz feedback from the secondary of T1 (foldout 20) is coupled to the emitter of paraphase converter Q22 (foldout 21) to stabilize its output. This maintains the secondary output of T1 at a precision 15 VAC 4.5 kHz.

Voltage monitoring circuit. The function of the voltage monitoring circuit is to deenergize power supply assembly 3A25 if either of the +30-VDC regulated, -30-VDC regulated, +28-VDC filtered, or +28-VDC unfiltered voltage does not stay within the required limits. The monitoring circuit consisting of Q9 through Q13, and associated components deenergizes assembly 3A25 by removing the ground path through Q13 for the coil of power supply disable relay A1K7. When the voltages are within tolerance, Q13 conducts and A1K7 (which controls the power supply) remains energized.

The emitter of Q11 is held at approximately +9.3 VDC by current flow from ground through CR6 and R29 to the +30-VDC supply. When either the +30 VDC goes more positive than +35 VDC or the -30 VDC becomes less negative than -25 VDC, voltage divider network R22 and R23 biases Q9 to saturation, grounding the cathode of CR7. Current from ground through CR7 and R27, to the +30-VDC supply lowers the base potential of Q11 below +9.3 VDC at its emitter. As a result, Q11 is cut off and the +30 VDC at R28 forward biases CR8. The base of Q12 swings positive enough to saturate the transistor causing the base of Q13 to approach +30 VDC. This large

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positive potential on the base cuts Q13 off; and A1K7 that was energized through Q13 is deenergized. In this manner, power is turned off when either +30 VDC or -30 VDC exceeds the circuit limits in the positive direction.

When the +30 VDC drops to less than +25 VDC or the -30 VDC rises to more than -35 VDC, the voltage network of R25 and R26 back biases Q10. With Q10 cut off, the +30 VDC on R24 forward biases CR5 and Q12 saturates connecting the +30 VDC on the collector of Q12 to the base of Q13. Again, A1K7 is deenergized and the power supply assembly is turned off.

Changes in +28 VDC filtered and unfiltered are sensed in a gate circuit consisting of CR10 and CR11 and R27. When the filtered +28 VDC drops below +20 VDC, the potential at the junction of R32 and R33 drops to less than +10 VDC. Diode CR10 conducts, applying this potential to the base of Q11, cutting it off. When Q11 is cut off, the +30 VDC across R28 forward biases CR8 and raises the potential at the base of Q12 to the saturation point. The +30 VDC at the collector of Q12 is connected to the base of Q13. Thus, Q13 is cut off and A1K7 is deenergized when the +28 VDC drops below +20 VDC.

The unfiltered +28 VDC is filtered by CR12, C7, and R36. When the unfiltered +28 VDC drops below +20 VDC, the potential at the junction of R34 and R35 drops to less than +10 VDC. Diode CR10 again applies this potential to the base of Q11, cutting it off. From this point on, the operation is identical to the operation of the filtered +28-VDC monitoring circuit.

Exercises (653):

1. Refer to foldout 21. What voltage input does the +30-VDC regulator use to provide a +30-VDC ±.15-volt precision voltage?

2. What is the function of R8 on foldout 21?

3. What effect does an increase in current through Q4 (foldout 21) have on the potential at the base of Q1?

4. Refer to foldout 21. What components maintain the base bias of Q3 at +9.3 VDC?

5. Refer to foldout 21. What components protect the +30-VDC regulator circuit from a short-circuit overload?

6. What signal is present at the collector of Q15 (foldout 21) during normal operation?

7. Refer to foldout 21. What is the function of C11?

8. What are the input and output of the flip-flop consisting of Q17 and Q18 in foldout 21?

9. What determines the switching of the flip-flop (Q17 and Q18) as seen in foldout 21?

10. Refer to foldout 21. What is the function of Q19?

11. Refer to foldout 20. What is the function of resistors A1R1 and A1R2?

12. Refer to foldout 21. How does the voltage monitoring circuit deenergize assembly 3A25?

13. What is the function of CR10, CR11, and R27 in foldout 21?

654. Trace a schematic diagram of the gyro spin motor power supply.

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Gyro Spin Motor Power Supply Assembly 3A20. The purpose of the gyro spin motor power supply is to provide 90-VAC, 375-Hz (±0.02 percent), 3-phase power for gyro spin motor excitation. The gyro spin motor power supply assembly is illustrated in foldout 22. Refer to this foldout and to foldout 20 during the course of our discussion of this power supply.

Recall that the output of flip-flop Q17-Q18 (foldout 21) is a 22-volt, peak-to-peak, 1.5-kHz signal. This signal is coupled from regulator electronics and power supply assembly 3A21 through C22 to terminal 1 of diode assembly CR1 (foldout 22). From CR1, the signal is applied to two flip-flop frequency dividers, each dividing the input signal frequency by 2, resulting in a 375-Hz output signal. The two flip-flops are identical, the first consisting of Q14 and Q15, and the second consisting of Q16 and Q17. The steering circuit uses CR1 and CR2 to control the conduction state of the flip-flop. The collectors are triggered by application of a negative signal to input capacitors C22 and C25. The third diode in the steering circuit provides a discharge path to minimize trigger loading. The low forward impedance of the diode insures fast recovery, whereas its high back impedance prevents shunting of the trigger pulse during the trigger period. In a static condition where Q15 is not conducting and Q14 is saturated, the collector of Q14 is at a minimum voltage and the collector of Q15 is at +30 VDC. The negative signal forward biases the diode connected to terminal 4 of diode assembly CR1, dropping the collector voltage of Q15. This negative going signal is coupled through C24 and R36 to the base of Q14. Transistor Q14 cuts off and its collector voltage rises to +30 VDC. The positive-going collector voltage of Q14 is coupled to the base of Q15 through C23 and R34, causing Q15 to begin conducting, rising to saturation. The new static condition of the flip-flop is Q14 cut off and Q15 saturated.

Transistor Q15 produces a square wave output that is half the frequency of the input signal, since Q15 conducts only during alternate negative input pulses. Capacitor C25 couples the 750-Hz square wave output from the collector of Q15 to terminal 1 of diode assembly CR2 in the second identical flip-flop circuit.

The 375-Hz square wave at the collector of Q17 is applied through emitter-follower Q18 and resistors R1 and R2 to the shaping circuit composed of Q1, Q2, and Q3. The RLC network in the input circuit of Q1 provides a clean sine-wave output from the 375-Hz square-wave input. Capacitor C1 acts as a high-frequency filter, and L1 and C2 form a 375-Hz resonant tank circuit.

Transistors Q1, Q2, and Q3 make up three stages of amplification with an overall gain of less than one due to degenerative feedback, from the collector of Q2 to the collector of Q1, through R4, R5, and R6. The 375-Hz sine-wave output at the emitter of Q3 is developed across the primary winding of T1. The secondary winding of T1, capacitor C6, and resistors R10 and R11 form a phase splitter that produces two signals that are 90° out of phase. Each signal is applied through an amplifier, a phase inverter, and a push-pull driver to a push-pull power amplifier. One amplifier consists of Q4 through Q8, and the other consists of Q9 through Q13. Since both power amplifiers are identical, we describe only one.

The value of R12, in the output of the phase splitter, is selected during dynamic test to assure a balanced input to both amplifier channels. The signal is amplified by Q4 and coupled through C10 to the base of Q5. Resistors R19, R20, R21, and R22 are the collector load for Q4 and set the initial operating level for the base of phase inverter driver Q5 and Q6. (The base of Q6 is held near AC ground by C11.) Transistor Q5 conducts when a positive signal is applied to the base, causing the emitter to become more positive. The collector of Q5 goes negative, and the collector of Q6 goes positive. The output from the collectors of Q5 and Q6 is transformer-coupled to the base of Q7 and Q8 (foldout 22). The outputs from push-pull driver amplifier Q7 and Q8 (output No. 1) and from Q12 and Q13 (output No. 2), 375-Hz sine waves, are 90° out of phase and are applied to power amplifier transistors Q3, Q4, Q5, and Q6 mounted on power supply assembly 3A25 (foldout 20). The push-pull operation of the power-amplifier transistors provides the current for the primary winding of T2 and T3. The voltage between terminals 5 and 6 of T2 and T3 controls the gain of the two amplifiers that generate the input, so that the voltage between the inputs of T2 and T3 is 90 volts. The secondary windings of T2 and T3 are connected in such a way that three voltages, 120° apart, are obtained. The connection is called Scott-T. From the transformers, the 3-phase power is applied to the gyro spin motors through A1K1 and A1K2. Relays A1K1 and A1K2 are energized for 60 seconds when the unit control mode selector switch is set to ALIGN.

Exercises (654):

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1. What is the voltage on the collector of Q15 (foldout 22) when it is not conducting?

2. Why is the output frequency of Q15 (foldout 22) half of the input frequency?

3. Refer to foldout 22. How much amplification do transistors Q1, Q2, and Q3 provide?

4. Refer to foldout 22. Which components make up the 375-Hz resonant tank circuit?

5. What is the difference in voltage between the inputs of 3A25T2 and T3?

6. When is the value of resistor 3A20R12 selected and what is its purpose? Refer to foldout 22.

7-3. Time Delay, Detector, and Flasher Circuits

In this section, we will discuss the go/no-go, pitch angle detector, time delay, and flasher assembly 3A8; level detector and time delay assembly 3A14; and the navigation set control 4-second time delay. The function of each of these assemblies was presented in Chapter 6; however, we briefly review the function of each assembly just before the circuit analysis is presented.

655. Using a specified schematic diagram, trace the go/no-go pitch angle detector, time delay, and flasher assembly.

Go/No-Go Pitch Angle Detector, Time Delay, and Flasher Assembly 3A8. This assembly (foldout 23) contains a heat 50-second time delay circuit, a 60-second time delay circuit, a flasher circuit for mode light flashing, a go/no-go circuit, and a pitch angle detector.

Heat 5-second time delay. This time delay prevents energizing the gyrocompass initiate relay for 50 seconds after the gyros reach operating temperature. When the gyros reach operating temperature, +28 VDC is applied to the 50-second time delay circuit. The voltage divider, consisting of R12 and CR15, establishes the emitter voltage of Q5 at approximately +12 VDC.

Capacitors C6 and C7 begin charging toward +28 VDC. The charge path for C6 and C7 is through R10, making one RC time constant equal to approximately 50 seconds. When C6 and C7 have charged to approximately 63.4 percent of the source voltage, or at the end of one time constant, Q5 is forward biased sufficiently to begin conducting. The resulting positive voltage change at the collector of Q5 causes Q4 to conduct. Transistor Q4 conducting provides added drive to the base of Q5, resulting in heavier conduction. The circuit (acting as a switch) saturates, causing the external relay in the emitter circuit of Q4 to energize, initiating gyrocompass align.

The 60-second time delay. This time delay delays the start of Af for 60 seconds after switching the mode selector switch to ALIGN. The time delay circuit is a modified bootstrap storage counter driven by a square wave input. The timing cycle is initiated by applying align +28 VDC to the collector of Q14.

The 115 VAC 4.5 kHz is applied through R46 to amplitude limiting diodes CR8 and CR9, which limit the peaks to approximately +1 VDC and -30 VDC. The 31-volt square wave is coupled through C18 to the RC time constant network consisting of R47 and R58 and C19. During the positive portion of the input square wave, C19 charges through CR10 and R47 and R48.

During the negative half-cycle, CR10 is back biased, and the charge on C19 does not change. The conduction level of Q14 is continually increasing because of the change in base voltage as the charge increases on C19. After approximately 60 seconds, the conduction level of Q14 provides enough positive voltage at the emitter to cause silicon control rectifier CR14 to conduct. Rectifier CR14, when conducting, provides a path to ground for the external connected fine align relay coil. C20 bypasses transient spikes that might trigger CR14 prematurely.

Flasher circuit. The flasher circuit controls the cycling of the flasher relay and the align light. The circuit consists of a control transistor and an RC network. The +28-VDC output controlled by the 50-second time delay of level detector, and time delay assembly 3A14 is applied to R2. Capacitor C1 charges through R2 toward +28 VDC until Q1 conducts energizing an external relay which applies -30 VDC to R3.

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C1 discharges and then charges through R3 toward -30 VDC and, when the charge becomes sufficiently negative, Q1 is cut off. The charge on C2 holds the external relay energized, and C1 continues to charge toward -30 VDC. When the charge on C2 is depleted, the external relay deenergizes, removing the -30 VDC. C1 begins charging toward +28 VDC, initiating a new cycle.

The time constant of R2 and C1 is such that Q1 again conducts in approximately 0.5 second, repeating a new cycle. Contacts of relay K30 (which is located on the computer) apply the -30 VDC through R3 to C1 while other contacts of the relay apply the +28 VDC to the align light or the navigation set control. This is clearly illustrated in foldout 16. The flasher-circuit cycling continues until the mode selector switch is turned to NAV, removing the +28-VDC input to the circuit.

Go/no-go circuit. The go/no-go circuit monitors the Z1 and Z2 gyro pick-off voltages and the 4.5-kHz excitation voltage, and initiates a system failure signal when any of the voltages deviate from a predetermined value. A no-go condition exists when the amplitude of either gyro pickoff voltage is too great or when the amplitude of the 4.5-kHz reference voltage is too low. Each go/no-go circuit consists of a gyro axis pickoff AC amplifier, a 4.5-kHz preamplifier, and a rectifier. The signal from both the Z1 and Z2 circuits is then applied through DC amplifiers to drive the relay control.

The Z1 gyro pickoff voltage is coupled through C3 to the base of Q2. Transistors Q2 and Q3 form a two-stage, high-gain, AC amplifier. The output signal from the collector of Q3 is coupled through isolation capacitor C5, rectified by CR1, and applied to the base of Q11. The Z2 gyro pickoff voltage is coupled through C9 to the AC amplifier consisting of Q6 and Q7. The signal output at the collector of Q7 is coupled through C17, rectified by CR4, and applied to the base of Q11.

The 15-VAC 4.5-kHz voltage is applied to the primary of isolation transformer T1. The secondary winding output of T1 is rectified by CR6 and applied to the base of Q8. During normal operation, Q8 is conducting heavily and the voltage at the collector is not positive enough to cause heavy conduction in Q11.

Transistors Q11, Q12, and Q13 are connected so that they detect a gross signal error condition. During normal operation, Q11 is biased at or near cutoff and Q12 and Q13 are conducting heavily. If either the Z1 or Z2 gyro pickoff signal exceeds approximately 810 millivolts, diode CR1 or CR4 produces a positive voltage at the base of Q11. The positive voltage causes heavy conduction in Q11 and produces a negative change at the collector of Q11, which is direct-coupled to the base of Q12.

The negative change cuts off Q12, causing the emitter voltage to become more negative. The high negative voltage at the junction of R44 and R45 in the emitter circuit of Q12 causes Q13 to drop conducting. When Q13 is cut off, the external relay connected to the collector of Q13 deenergizes, and a system failure signal is produced.

If the 15-VAC 4.5-kHz coltage falls below approximately 12 volts, Q8 cuts off and its collector voltage becomes more positive. The positive voltage appears, through CR5, at the base of Q11. The positive voltage causes heavy conduction in Q11, cutting off Q12 and Q13. This action produces the system failure signal.

Pitch angle detector. The pitch angle detector circuit generates a DC voltage proportional to the pitch synchro output. This DC voltage controls the gain of the outer roll linear preamplifier. The circuit contains a high-impedance input isolation transformer, an AC amplifier, a bridge rectifier, and a low-impedance output emitter-follower. Refer to foldout 9 to see how the pitch angle detector fits into the system.

The 400-Hz pitch synchro transmitter input signal is applied to T2 (see foldout 23). As the pitch angle increases toward 90°, the amplitude of the input signal increases. The output from T2 is applied to AC amplifier Q9. Resistors R29 and R30 form a voltage divider that establishes the DC operating level at the base of Q9.

Emitter resistor R31 is bypassed by C13, leaving the primary winding of T3 as the only AC loan in the emitter circuit of Q9. The output from the secondary winding of T3 is rectified by bridge rectifier CR7 and applied to a double-pi filter. The filtered voltage applied to the base of Q10 contains less than 8 millivolts peak-to-peak ripple. The pitch angle detector output is taken from emitter-follower Q10.

Exercises (655):

1. What is the function of R12 and CR 15 in foldout 23?

2. What is the function of CR8 and CR9 in foldout 23?

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3. Refer to foldout 23. What controls the frequency at which the align light flashes?

4. When a voltage deviates from a predetermined value, what circuit initiates the system failure signal?

5. What is the function of C17 in foldout 23?

6. In what condition is Q13 when the system failure signal is produced (foldout 23)?

7. The pitch angle detector circuit generates a DC voltage proportional to which synchro output?

8. What is the AC load in the emitter circuit of Q9 in foldout 23?

9. What happens to the input signal amplitude as the pitch angle increases toward 90°?

10. Which time delay circuit delays the start of Af?

11. How is the timing cycle of the 60-second time delay started?

456. Trace a schematic diagram of the level detector and time delay assembly and cite the purpose of specified components.

Level Detector and Time Delay Assembly 3A14. This assembly consists of four separate circuits: The level detector, level 50-second time delay, 75-second time delay, and power-interrupt circuit. The power-interrupt circuit was discussed earlier. We will discuss the remainder of these circuits separately with the aid of foldout 19.

Level detector. The level detector compares the Ay sec ϕ signal to +10 VDC and to -10 VDC during gyrocompass align mode. If the Ay sec ϕ signal is within these references, the gyrocompass align phase is completed. One of the two level detector channels will cause relay control amplifier transistor Q19 to conduct, energizing K29 and initiating the level 50-second time delay.

Transistors Q13, Q15, and Q17 control Q19 when the signal is less than +10 VDC. Transistors Q14, Q16, and Q18 control Q19 when the signal is greater than -10 VDC. Since both detector channels are identical, only the operation of the positive detector channel is described.

The Ay sec ϕ input signal is applied through R11 to double anode zener diode CR10, which limits the input signal voltage to maximum $\pm$ 11 VDC. Transistors Q13 and Q15 are differential amplifiers, referenced to the +10 VDC precision voltage. When the input signal is less than +10 VDC, the reference +10 VDC applied through CR5 to the base of Q15 causes the transistor to conduct. This results in a voltage at the emitter of Q13 that is more positive than its base voltage holding Q13 at cut off. The negative change in voltage at the collector of Q15 is sufficient to forward bias A2CR1 and cause level detector Q17 to conduct. The emitter of Q17 is held at approximately +18 VDC by zener diode A2CR2. The positive change at the collector of Q17 is felt at the junction of A2CR3, A2R7, and the base of Q19. Transistor Q19 conducts, energizing external relay K29 in the collector circuit.

When the input signal is greater than +10 VDC, the voltage at the base of Q13 is sufficient to overcome the emitter bias, and Q13 conducts. The emitter of Q15 becomes more positive than the base and is cut off. Because diode A2CR1 is then back biased, Q17 ceases to conduct. When Q17 is cut off, the junction of A2CR3 and A2R7 becomes negative and Q19 ceases to conduct, deenergizing K29.

Level 50-second time delay. This time delay applies +28 VDC to the flasher circuit 50 seconds after leveling has been indicated by the level detector circuit. Transistors Q4, Q5, and Q6 and zener diode CR2 comprise the 50-second time delay circuit.

The Af +28 VDC is available from the contacts of the output level detector relay and is applied to the RC network composed of A1R4 and C1. Capacitor C1 begins charging toward the input +28 VDC. Transistor Q4 is a compound-connected transistor with the emitter returned to ground through the emitter

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base junction of Q5, zener diode CR2, and the emitter base junction of Q6. When the charge on C1 reaches approximately +8.4 volts (about 50 seconds after +28 VDC is applied), the base of Q4 becomes sufficiently positive to cause zener diode CR2 to break down. Q4 and Q5 conduct and drive Q6 to saturation, energizing externally connected relay K21. The energized relay indicates the completion of gyrocompass align by applying +28 VDC to the align flight flasher circuit. Diodes A1CR2 and A1CR3 and A1R3 in the base circuit of Q4 provide a discharge path for C1 when the +28 VDC input is removed. The back resistance of the two diodes, in series, forms an extremely high shunt resistance across A1R4 so that the charge time of C1 is not appreciably affected when the +28 VDC is present.

The 75-second time delay. This circuit delays the start of Gc for 75 seconds after the start of Af. The 75-second time delay circuit comprises transistors Q7 through Q12. Transistors Q7 through Q10 form a high-gain integrating amplifier. When the input is applied to Q7, the output voltage at the collector of Q10 increases linearly with respect to time, maintaining a constant charge current and producing a linear output.

The 75-second time delay period is initiated when +28 VDC is applied to A4CR3 and A4CR4, which limits the input signal at the base of Q7. Q7 and Q8 form a differential and, with no input, Q8 is the only transistor conducting. Q7 conducts when its base becomes positive with respect to the emitter, causing the current through Q8 to decrease. The output signal at the collector of Q7 is direct-coupled to the base of Q9. The difference signal present at the collector of Q8 is direct-coupled to the emitter of Q9. When the difference between the voltages at the collectors of transistors Q7 and Q8 is such that the base potential of Q9 becomes negative with respect to the emitter, Q9 conducts.

The collector of Q9 is directly connected to the base of Q10, and conduction of Q9 causes Q10 to conduct. When Q10 conducts, the collector voltage decreases, maintaining a constant charge current for integration feedback capacitors C2 and C3. The collector output from Q10 charges linearly from +30 VDC toward -30 VDC. This signal is applied through A3CR1 and A3R10 to the base of Q11. When the negative going voltage at the base of Q11 exceeds the breakdown voltage of zener diode CR3, Q11 and Q12 conduct, energizing relay A28K11. Resistor A3R9 and capacitor A3C1, in the collector circuit of Q10, form a filter network which eliminates high-frequency transients. Diode A4CR1 in the base circuit of Q7 provides a rapid discharge path for C2 and C3.

Exercises (656):

1. Which transistors control transistor Q19 when the input signal is less than +10 VDC?

2. What components in foldout 19 provide a discharge path for C1 when the +28 VDC input to Q4 is removed?

3. What type of circuit do transistors Q7 and Q8 (foldout 19) form?

4. In foldout 19, when does transistor Q9 conduct?

5. In foldout 19, what is the function of A4CR1?

6. When the voltage on the base of Q4 is approximately 8.4 volts, what happens to CR2 and the transistors in the circuit?

7. What happens to level detector input voltages greater than 11 VDC?

8. When relay K29 is energized what is the condition or state of Q19?

657. Trace a designated schematic diagram of the 4-second time delay and state the purpose of specified components.

Navigation Set Control 4-Second Time Delay. A 4-second time delay located in the navigation set control (fig. 7-2) controls relay K17 in the navigational computer. When K17 is deenergized, each of the DC amplifiers discussed in Chapter 5 (foldout 1) is shunted by a 2-kilohm resistor. The shunt resistance provides protection to the DC amplifiers during initial power turn-on and when a power interrupt occurs during navigate. When K17 is energized, the shunt is removed.

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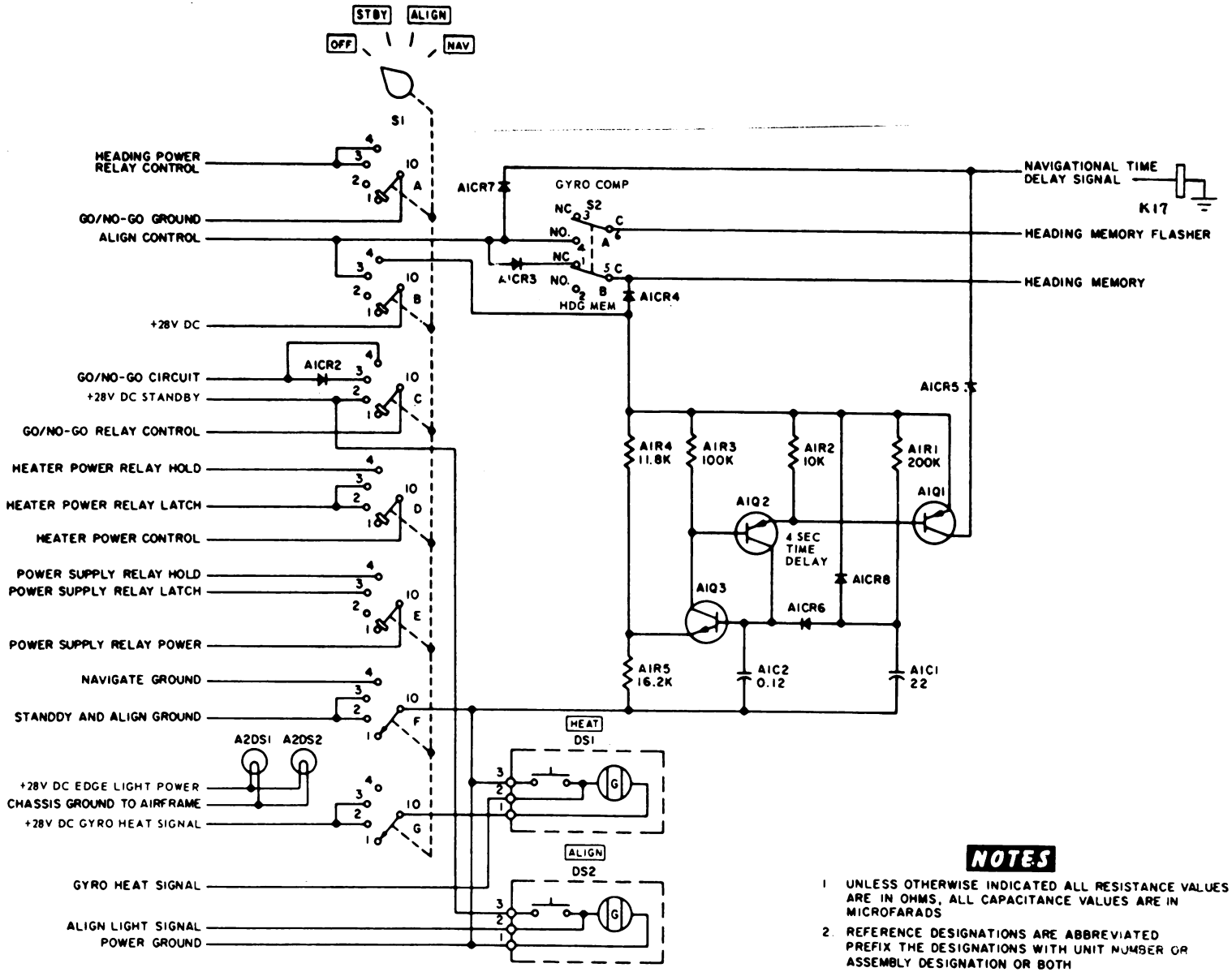

Figure 7-2. Navigation set control 4-second time delay.

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When the control unit mode selector switch is set to ALIGN, 28 VDC is applied through A1CR7 to K17. The 4-second time delay provides the navigational time delay signal 4 seconds after the control unit mode selector switch is set to NAV. When the control unit mode selector switch is set to NAV, +28 VDC is applied through switch S1B4 to the junction of A1CR4 and A1R4. Resistors A1R4 and A1R5 form a voltage divider that sets the emitter voltage of A1Q3 to approximately +16 VDC. Capacitor A1C1 charges through A1R1 toward +28 VDC. After approximately 4 seconds, the charge on A1C1 is sufficient to forward bias A1Q3 into conduction. When A1Q3 conducts, the negative change in voltage at its collector causes A1Q2 to conduct. The resultant negative voltage at the emitter of A1Q2 causes A1Q1 to conduct. The conduction of A1Q1 provides +28 VDC through A1CR5 energizing K17 and removing the resistive shunts from the DC amplifiers.

Resistor A1R1 and capacitor A1C1 compose an RC time constant circuit. Capacitor A1C1 charges to 16.6 volts in 4 seconds, providing the base drive for A1Q3. Diode A1CR8 provides a rapid discharge path for C1 if the +28-VDC supply is interrupted, resetting the 4-second delay. Diodes A1CR4 and A1CR5 block +28 VDC from the time delay circuit during the ALIGN mode.

Exercises (657):

1. In figure 7-2, what is the function of A1R4 and A1R5?

2. What is the purpose of diodes A1CR4 and A1CR5 (fig. 7-2)?

3. Which components determine the delay time?

4. How is the time delay reset if the 28-VDC power supply is interrupted?

7-4. Gimbal Positioning Servoamplifier

In the previous chapter, we presented the various gimbal positioning loops, their function, and operation. In this section, we present a circuit analysis of the servoamplifier that are an importation part of these loops.

658. State the purpose of the gyroscope preamplifier assembly.

Gyroscope Preamplifier Assembly. One gyroscrope amplifier assembly is mounted on the side of each of the the two gyros. Note in figure 7-3 that this assembly contains an amplifier, resistive network, and terminals for electrical connection to the gyro. The amplifier provides amplification of the gyro gimbal pickoff signals and routes them to the azimuth resolver. The resistive network is necessary, since it provides the gyroscrope electronics and the electrical connections to the gyroscrope.

Exercise (658):

1. Why must a preamplifier be mounted on the side of each gyro?

659. Trace a specific schematic diagram of the inner roll and pitch servoamplifier.

Inner Roll and Pitch Servoamplifier Assembly 3A3. Assembly 3A3 contains two separate amplifier circuits: the inner roll servoamplifier and the pitch servoamplifier. These are illustrated in foldout 24. The amplifiers provide drive signals for their respective servomotors. The inputs to the servoamplifiers are the 4.5-kHz outputs from the platform azimuth resolver. Since the operation of these servoamplifiers is identical, only the inner roll servoamplifier section is described in detail.

The 4.5-kHz azimuth resolver error signal is applied through C1 to the base of Q1. Transistors Q1 and Q2 are high-gain AC amplifiers. The amplifier signal out of Q2 is applied through C4 and R8 to demodulator transistor Q4. A 4.5kHz reference signal is applied through C3 and R9 to the base of isolation preamplifier transistor Q3. The amplifier reference signal is applied to the base of Q4. (Note that the output of Q3 is also applied to Q16 in the pitch servoamplifier.) Q4 acts as a phase-sensitive demodulator whose output is proportional to the phase difference between the reference signal at its base and the amplified error signal at its emitter. The demodulated output is a DC signal that is

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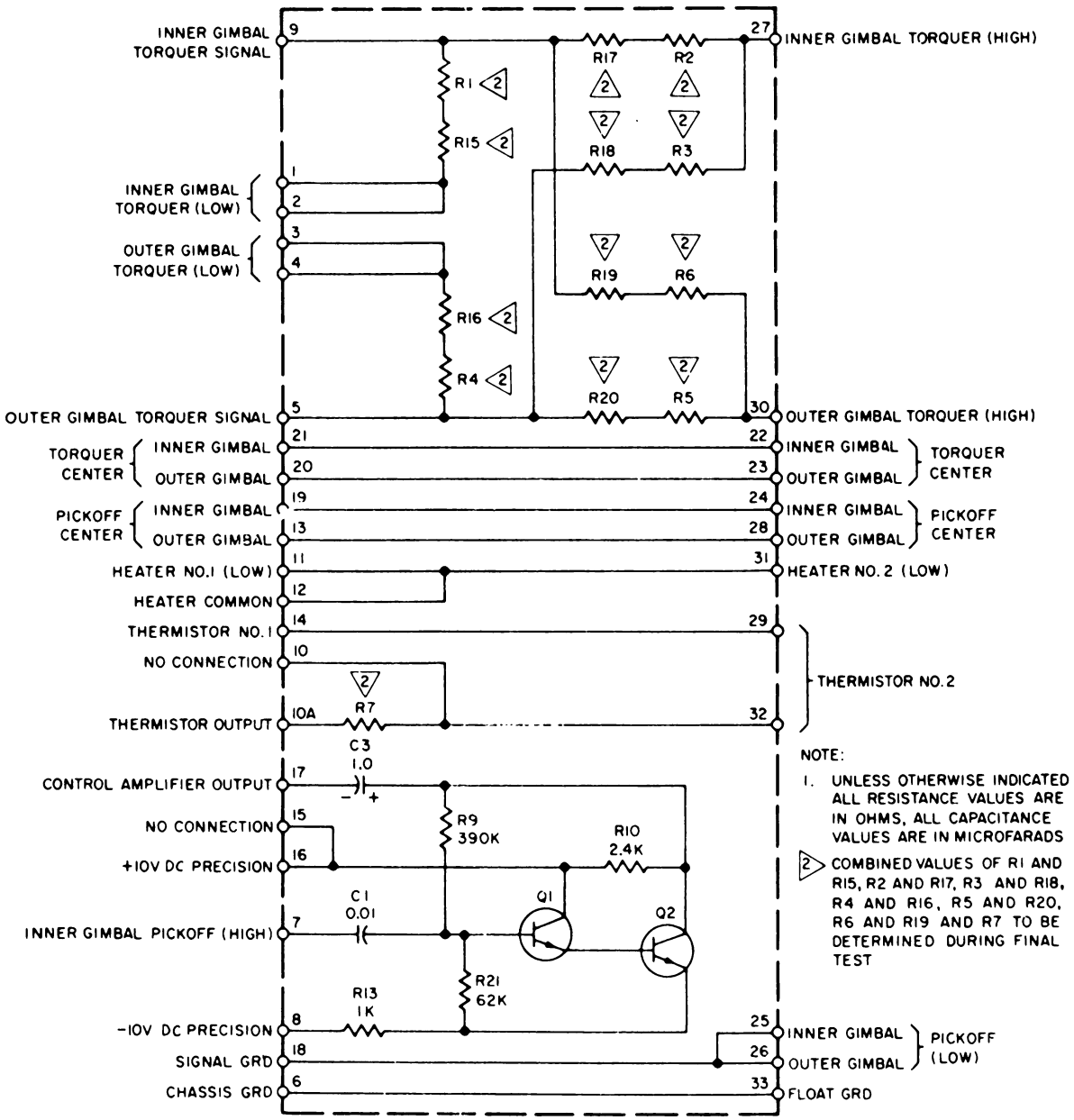

Figure 7-3. Gyroscope preamplifier assembly.

filtered by R12, C5, and R13 and then applied to the base of Q5. Transistors Q5, Q6, and Q7 form a high-gain, feedback-stabilized, DC amplifier. C7, an integral gain capacitor in the feedback circuit, allows the DC error signal to be integrated. This stabilizes the output from the DC amplifier and thus eliminates any static position error of the inner roll gimbal.

During Ac, integral gain capacitor C7 is bypassed by external relay action to eliminate high-gain characteristics at low frequencies. The output from Q7 is applied to an external twin-tee filter network. The twin-tee filter is designed to reject any 375-Hz ripple present on the DC signal. The filtered signal is applied to 400-Hz modulator transistor Q8. The filtered DC signal is modulated at a 400-Hz rate and applied to transistor amplifier Q9.

The amplified DC signal out of Q9 is applied to a paraphase converter formed by Q10, Q11, and T1. The single-phase 400-Hz signal is converted to two signals of equal amplitude and 180° out of phase with each other. The two signals are coupled through T1 to the bases of push-pull driver transistors Q12 and Q13. The outputs of Q12 and Q13 drive power transistors

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A2Q5 and A2Q6 (mounted on integrator shaft assembly 3A24). The outputs of A2Q5 and A2Q6 provide the drive signals for the inner roll servomotors.

Exercises (659):

1. What are the inputs to the servoamplifiers illustrated in foldout 24?

2. To what is the output of Q4 in foldout 24 proportional?

3. In foldout 24, transistors Q5, Q6, and Q7 form a high-gain, feedback-stabilized, DC amplifier. What component is used as the integral gain capacitor?

4. During what align submode is integral gain capacitor C7 (foldout 24) bypassed by external relay action?

660. Trace a designated schematic of the outer roll servoamplifier.

Outer Roll Servoamplifier Assembly 3A1. This assembly provides the control signal to the outer roll gimbal of the platform. Note in foldout 25 that it consists of a linear channel and nonlinear feed-forward rate channel. The linear channel contains a cascade AC preamplifier (with a nonlinear gain network), a 4.5-kHz demodulator, a DC amplifier, a 400-Hz modulator, and a power amplifier. The gain of the linear channel is controlled by a variable attenuator connected to the input, the amount of attenuation varying with the aircraft pitch angle. The nonlinear rate channel consists of a 4.5-kHz demodulator and a DC amplifier. During Ac the input signal is obtained from the outer roll synchro; therefore, the outer roll gimbal is positioned to the approximate attitude of the aircraft, and during this phase of operation, the integral gain capacitor is shorted to maintain loop stability. During Af, the input signal is obtained from the inner roll synchro. The nonlinear feedback network, which is approximately the inverse cosine of pitch angle, adjusts the gain of the linear channel in such a manner that the inner and outer roll coupling is made independent of pitch angle. As the pitch angle passes through 90°, a flipping operation (rotation of the outer roll gimbal through 180°) is accomplished. The nonlinear channel provides an accelerating torque to the outer roll gimbal during the initial flipping phase and provides a braking torque during the final phase.

The inner roll synchro signal input is applied to the linear channel through C2 and R11 to the base of Q1. Transistors Q1, Q2, and Q3 form a variable gain AC amplifier. The gain is controlled by feedback, and the amount of feedback is determined by C5, R13, and the variable attenuator network. The impedance of the variable attenuator network varies with the DC input from the pitch angle detector. The pitch angle detector signal is applied through L1 to the attenuator network. When the DC input is maximum, CR1 through CR4 are back biased, reuslting in no shunt path across C5 and R13. When no shunt path exists across C5 and R13, feedback voltage is maximum and amplifier gain is minimum.

As the DC input changes from maximum to minimum, CR1 through CR4 conduct, in sequence, as they become forward biased. As a diode conducts, a shunt path exists across C5 and R13 through the diode cathode resistors and C3. When the DC input is minimum, four shunt paths exist across C5 and R13, resulting in minimum feedback voltage and maximum amplifier gain.

The output of Q3 is applied through C6 and R33 to the emitter of demodulator transistor Q5. A 4.5-kHz reference voltage for the demodulator is amplified by Q4 and applied through R23 to the base of bisymmetrical transistor Q5. The amplitude of the DC output signal at the collector of Q5 is proportional to the input signal applied to the emitter. The polarity of the input signal is determined by the phase relationship between the reference signal applied to the base and the input signal applied to the emitter. The DC output signal is filtered by filter network R24, C8, and R25 and applied to differential amplifier transistor Q6.

Transistors Q6, Q7, and Q8 form a high-gain DC amplifier employing stabilization feedback. The feedback path is from the collector of Q8 through integral gain capacitors C11 and R30 (during ALIGN, C11 is shorted by the external integral gain relay, making Q6, Q7, and Q8 a linear DC amplifier with purely resistive feedback). Feedback capacitor C11 is shunted by R34 (which establishes the DC gain of the amplifier), and zener diodes CR6 and CR7

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(which limit the amplifier output). The output of the DC amplifier is applied to the emitter of modulator transistor Q13 through R49 and R50. A 400-Hz modulation voltage is applied to the base of Q13. The DC signal voltage at the emitter of Q13 is modulated (chopped) at a 400-Hz rate and applied through C19 and R51 to the base of Q14.

Transistors Q14, Q15, Q16, Q17, and Q18 form a driver circuit that drives power output transistors A2Q7 and A2Q8 in integrator shaft assembly 3A24 (discussed and shown later in foldout 31). The 400-Hz signal is amplified by Q14 and applied to Q15 and Q16, which operate as a paraphase converter. The negative half-cycle of signal voltage at the base of Q15 causes a decrease in current through Q15 and primary winding D to E of T1. The decrease in current causes a negative change in the voltage at the junction of R55 and R56. This results in an increase in current through Q16 and primary winding F to E of T1. The positive half-cycle of signal voltage at the base of Q15 causes an increase in current through Q15 and a decrease in current through Q16. The alternate change in current in the primary of T1 induces amplitude-balanced signals, 180° out of phase, in the secondary windings. This push-pull signal is applied to driver transistors Q17 and Q18. The outputs of Q17 and Q18 are applied to power transistors A2Q7 and A2Q8 in integrator shaft assembly 3A24.

The inner roll input signal is also applied through C13 and R37 to the emitter of demodulator transistor Q9 in the nonlinear rate channel. The 4.5-kHz reference voltage is applied through R36 to the base of Q9. The output of demodulator transistor Q9 is a DC signal of the same polarity and phase relationship as the output of linear channel demodulator transistor Q5. The DC output of Q9 is filtered by R38, C14, and R39 and applied through C15 to a high-gain DC amplifier. Note that this DC amplifier also uses stabilization feedback.

The DC amplifier is comprised of transistors Q10, Q11, and Q12, with feedback from the collector of Q12 through R44 to the B1 base of Q10. When the inner roll rate input is sufficient to overcome the breakdown potential of zener diode CR9 or CR10, the nonlinear rate channel output is summed with the linear channel output at the emitter of modulation transistor Q13. The summed signal at the emitter of Q13 then becomes the input to the power amplifier, which furnishes the drive for the outer roll servomotors.

Exercises (660):

1. The gain of the linear channel (foldout 25) is controlled by a variable attenuator at the input. What determines the amount of attenuation?

2. What causes the impedance of the variable attenuator network in foldout 25 to vary?

3. In foldout 25, what is the relationship between the amplitude of the DC output signal at the collector of Q5 and the input signal applied to the emitter?

4. During ALIGN, what type signal is present at the junction of R50 and C19 in foldout 25?

5. What effect does a decrease in current through the primary of T1 (foldout 25) have on the current through Q16?

6. What is the relationship between the output of Q9 (foldout 25) and the output of Q5?

7. Refer to foldout 25. Transistors Q1, Q2, and Q3 employ what?

8. Refer to foldout 25. Where are the outputs from the linear and nonlinear channels combined or summed?

9. Which transistors (foldout 25) provide the outer roll servo motor torque?

661. Trace a schematic diagram of the slaving amplifier and cite the purpose of specified components.

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Slaving Amplifier. The slaving amplifier generates a DC input voltage for the Z-torquer summing amplifier and an AC input voltage for the servoamplifier. These two voltages are proportional to the difference between true heading and the platform azimuth orientation.

The input signal is amplified by Q1 and direct-coupled to the base of Q2 (see upper left of foldout 18). Transistors Q2 and Q3 and transformer T2 form a phase inverter whose output is applied to opposite ends of a full-wave demodulator. When the current through Q2 increases, the resultant positive change in voltage at the junction of R6 and R7 causes a decrease in current through Q3. The collector loads for Q2 and Q3 are the halves of the primary winding of T2. When the current through Q2 decreases, the current through Q3 increases. The alternate increase and decrease of current through Q2 and Q3 results in a balanced-to-ground output from the secondary of T2. This balanced signal is applied to the full-wave demodulator. The demodulator consists of reference transformer T1, zener diodes CR1 and CR4, and diode bridges CR2 and CR3. On each half-cycle of the reference voltage, either diode bridge CR2 or CR3 conducts. When either diode bridge conducts, the voltage at its input is applied across C4 and C5, the filter input capacitors. The output is further filtered by R10, R12, and R13, and C6, C7, and C8. The voltage at the junction of R11 and R14 is filtered by C9 and C10. The voltage developed across R13 is applied through R15 and R16 to the emitter of Q4. The base of Q4 is driven by a 7.5-VAC 4.5-kHz reference which modulates the emitter voltage. During the negative half-cycle of the reference voltage, Q4 conducts heavily and effectively grounds its emitter. When this condition exists, there is no output. During the positive half-cycle of the reference voltage, Q4 is cut off and the voltage at its emitter is coupled through C12 to two stages of amplification, consisting of Q5 and Q6. Capacitor C13 is the coupling capacitor for the output of Q6.

Exercise (661):

1. In foldout 18, what are the collector leads for Q2 and Q3?

2. Refer to foldout 18. What is the purpose of T1, zener diodes CR1 and CR4, and CR2 and CR3?

662. Trace a specified schematic of the true heading servoamplifier.

True Heading Servoamplifier. The true heading servoamplifier is shown at the bottom of foldout 18. Inputs to this circuit are the heading error signal and the true heading servotachometer output. The output is the drive signal for the true heading servomotor. The two input signals are summed at the junction of R44 and R45 and applied to the base of Q15. The amplified signal at the collector of Q15 is direct-coupled to the base of Q16. Transistors Q16 and Q17 and transformer T4 operate as a phase inverter whose output drives compound-connected push-pull transistors Q18, Q20, Q19, and Q21. A negative half-cycle at the base of Q16 causes a decrease in current through Q16 and its half of the primary of T4. The decrease in current causes a negative change in voltage at the junction of R49 and R50. This change, coupled through C23, causes an increase in current through Q17 and its half of the primary of T4. A positive half-cycle at the base of Q16 causes an increase in current through Q16 and a decrease in current through Q17. The alternate change in current in the primary of T4 induces a voltage in its secondary that drives push-pull transistors Q18 through Q21. Bias for Q18 and Q19 is provided by the voltage drop across CR9 and CR10.

Exercise (662):

1. In foldout 18, what signals does the true heading servoamplifier utilize to create the drive signal for the true heading servomotor?

2. Refer to foldout 18. What signals are applied to the base of Q15?

3. How is bias for Q18 and Q19 (foldout 18) developed?

663. Using a schematic diagram, trace the azimuth servoamplifier and caging amplifier.

Azimuth Servoamplifier. Any misalignment about the azimuth axis between the lower YZ1

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gyro float and the gyro case is sensed by the Z-axis pickoff as a 4.5kHz amplitude-modulated error signal. The magnitude of the error signal voltage is proportional to the degree of misalignment. The error signal is either in phase or 180° out of phase with the 4.5-kHz excitation voltage, depending upon the direction of the angular misalignment. This signal is applied to the azimuth servoamplifier that consists of an AC premaplifier, a 4.5-kHz demodulator, a DC amplifier, a 400-Hz modulator, and a power amplifier. The output then drives the azimuth servomotors, repositioning the azimuth gimbal to null the error signal.

The YZ1 gyro 4.5-kHz pickoff signal is coupled through C1 (see upper left of foldout 26) and amplified by Q1 and Q2. The amplified output at the collector of Q2 is coupled through C3 to the emitter of demodulator transistor Q4. A 4.5-kHz reference signal is coupled through C4 to the base of Q3, amplified, and applied through R11 to the base of Q4. When the input signal is in phase with the reference input, Q4 conducts during the positive half-cycle of the reference voltage. When Q4 conducts, its emitter is grounded and there is no output from the demodulator. When the Q4 is cut off, the voltage at the emitter, which is the negative half-cycle of the input signal, is filtered by a network consisting of R12, C5, and R13, and applied to DC amplifier Q5. When the input signal is out of phase with the reference input, the resultant demodulator output is the positive half-cycle of the input signal.

The high-gain DC amplifier consists of Q5, Q6 (Darlington connected), and Q7. Note the feedback from the collector of Q7 to the B1 base of Q5 through integral gain capacitor C7 and R16 and R14. This feedback through C7 provides a smooth response to any rapidly changing input signal. During INS alignment, C7 is short circuited to provide a DC output that responds more rapidly to the input signal.

The DC amplifier output is applied through R24 to the emitter of modulator transistor Q8, where it is modulated at 400 Hz. The modulation voltage is 6.3 VDC 400 Hz, which is applied to the base of Q8. The modulated signal is applied through AC amplifier Q9, paraphase converter Q10-Q11, and T1 to push-pull power amplifier driver Q12-Q13. Transistor Q9 amplifies the modulated signal before it is applied to the paraphase converter. The positive half-cycle of input voltage at the base of Q10 causes an increase in current through Q10 and primary winding D to E of T1. The resultant positive change in voltage at the junction of R29 and R30 causes a decrease in current through Q11 and primary winding F to E of T1.

The negative half-cycle at the base of Q10 causes a decrease in current through Q10, which results in an increase in current through Q11. The alternate increasing and decreasing of current through Q10 and Q11 results in balanced-to-ground signals, 180° out of phase with respect to each other, from the secondary windings of T1. These signals are applied to push-pull driver amplifier transistors Q12 and Q13. The 400-Hz output signals are applied to power transistors A2Q1 and A2Q2, mounted in integrator shaft assembly 3A24 (discussed and shown later in foldout 31).

Azimuth Caging Amplifier. The 4.5-kHz error signal from the redundant upper XZ2 gyro pickoff is applied to the azimuth caging amplifier channel. This channel comprises an AC preamplifier, a demodulator, a positive DC amplifier, and a negative DC amplifier. The caging amplifier output drives the XZ2 gyro Z-axis torquer, caging the gyro to its own azimuth output.

The Z1 and Z2 gyro pickoff signals are summed at the junction of R34 and R35 and applied to the base of Q14. (See lower left of foldout 26.) Transistors Q14, Q15, and Q16 form a high-gain, feedback-stabilized, AC amplifier whose output is developed across the primary winding of T2. Capacitor C16 bypasses R43 so that the primary winding of T2 is the only AC load in the collector circuit of Q16. Resistor R43 establishes the collector DC level.

The output from the secondary of T2 is applied to a demodulator consisting of T3, zener diode CR2, and diode bridge CR3. Current flows through diode bridge CR3 only when pin B to pin A exceeds the breakdown voltage of zener diode CR2. When diode bridge CR3 is conducting, the voltage at pin B of T2 is developed across filter input capacitor C17. When pin B of T3 is positive with respect to pin A, diode bridge CR3 is back biased and there is no demodulator output.

The output from the demodulator is filtered by C17, R44, and C18 and amplified in complementary transistors Q17 and Q18. When the demodulator output is positive, Q17 conducts and causes Q19 to conduct. The emitter of Q19 is returned to ground through the Z2 torquer coil. When the demodulator output is negative, Q18 conducts and causes Q20 to conduct. The collector of Q20 is returned to ground through the Z2 gyro torquer coil. Thus, the direction of current flow through the Z2 gyro torquer coil is determined by the polarity of the demodulator output voltage.

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Exercises (663):

1. In the high-gain DC amplifier (Q5 through Q7 in foldout 26), why is C7 short circuited during INS alignment?

2. In foldout 26, where is the voltage developed when diode bridge CR3 is conducting?

3. Refer to foldout 26. Where does modulation of the DC amplifier output of the azimuth servo amplifier take place?

4. When current flow decreases through Q10, what happens to current in Q11? Refer to foldout 26.

5. What component provides the AC load for the collector of Q16 (foldout 26)?

6. How is the collector of Q20 grounded?

7-5. Velocity and Position Integrating Circuits

In this section, we discuss the integrator shaft assembly and the various amplifiers used in the velocity and position circuits. We highly recommend that you review briefly the function of these circuits presented in Chapter 6 before you begin study of the circuit analysis.

664. Trace a schematic diagram of the accelerometer restoring amplifier assembly and cite the purpose of specified components.

Accelerometer Restoring Amplifier Assembly 3A7. This assembly contains three separate servoamplifier channels that supply DC restoring (torquing) currents to the X-, Y-, and Z-accelerometers. Each channel consists of three sections: preamplifier, demodulator, and DC output amplifier. These are illustrated in foldout 27. The circuit function is to supply current which maintains a null between the acceleration torque and the magnetic restoring torque. (Recall that the restoring torque, created by an electromagnet and a permanent magnet inside the accelerometer, is proportional to current through the torque coil.) The input to each restoring amplifier channel is a 4.5-kHz pickoff error signal from its respective accelerometer. Operation of the three restoring amplifier channels is identical; therefore, only the X-accelerometer restoring amplifier channel will be described in detail.

The 4.5-kHz error signal from the X-accelerometer is applied to the base of Q1 through C1 and R2, and amplified by AC amplifier transistors Q1, Q2, and Q3. Frequency stability feedback in this AC amplifier is provided from the collector of Q3 through R8 and R3 to the base of Q1. The output signal from Q3 is applied through C3 and R11 to the emitter of demodulator transistor Q4.

A 4.5-kHz reference voltage is coupled through C14, amplified in Q14, and applied through R10 to the base of demodulator transistor Q4. (Note that the 4.5kHz reference is also applied to demodulator transistors Q15 and Q25 in the other two amplifier channels.) The output of the demodulator Q4 is a DC voltage whose amplitude is proportional to the error signal applied to the emitter. The polarity of the output depends upon the phase difference between the reference voltage on the base and the error signal on the emitter. The 4.5-kHz ripple on the DC output signal at the emitter of Q4 is filtered by R12 and R13 and C4 before it is applied to the base of differential amplifier transistor Q5.

Transistors Q5 through A10 comprise a high-gain, temperature-compensated, feedback-stabilized, DC amplifier. Transistor Q5 is connected so that the voltage at its emitter remains nearly constant because of the action of the C2, B2, and E2 section. Feedback network capacitors C10 and C8 and resistors R21 through R23, between the collector of Q10 and the base of Q5, provide a gain control for the DC amplifier, and Q9 provides temperature stability. The DC output is applied to the X-accelerometer torquer.

Exercises (664):

1. What is the function of the accelerometer-restoring amplifier?

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2. How is frequency stability provided for Q1, Q2, and Q3?

3. Refer to foldout 27. What is the purpose of Q30?

4. What are the sections that make up each channel?

5. How is the output polarity of Q15 determined?

665. Trace a schematic diagram of the DC amplifier assemblies.

DC Amplifier Assemblies 3A4, 3A5, 3A10, and 3A11. These DC amplifiers are used in all of the integrator circuits within the computer. Refer to foldout 28 for a schematic diagram of a DC amplifier assembly. Each DC amplifier consists of an AC section for low-frequency signal amplification and a differential DC amplifier section which amplifies both the output of the DC section and the unamplified high-frequency portion of the input signal. The input signal contains slow- and fast-changing DC components which are applied simultaneously to both the AC amplifier section and the DC amplifier section. The pure DC component of the input signal is converted to a 400-Hz square wave and amplified by the DC section. The AC amplification results in greater amplifier stability for low-level input signals. The output of the AC section is then restored to a DC level, combined with the fast-changing DC component of the input signal, and amplified in the DC section. The combination of a DC amplifier preceded by an AC amplifier reduces the effect of drift that would introduce spurious signals of the same nature as the signal being amplified. The DC signal input is applied to R1 and limited in amplitude to +0.7 VDC by CR2 and -0.7 VDC by CR1. The slow-changing DC component of the input signal is coupled through the low-pass filter formed by A1R1 and A1R2 and A1C1. Chopper G1, excited by a 400-Hz voltage, chops the signal to ground at the junction of A1R2 and A1C2, converting the DC signal to a 400-Hz square wave. The 400-Hz input to G1 causes the contacts at pins 1 and 6 to vibrate at 400 Hz. This converts the straight DC to a pulsating DC. All vibrators in this system operate in this manner.

The 400-Hz signal is then applied through A1C2 and A1R3 to the base of A1Q1. A1Q1, A1Q2, A1Q3 are Darlington configuration transistors which form three grounded emitter AC amplifier stages. The AC signal is amplified by A1Q1, direct-coupled to the base of A1Q2, amplified, and direct-coupled to the base of A1Q3.

Feedback from the emitter of A1Q2 through A1R6 to the base of A1Q1 establishes the AC gain of the first two stages. The DC gain is very low because of the bypass action of A1C4 in the emitter circuit of A1Q2. A resistive and capacitive decoupling network in the collector circuit of A1Q1 and A1Q2 keeps AC signal voltage fluctuations from affecting the DC supply voltage. Resistor A1R11 and capacitor C2 establish the AC gain of final AC amplifier stage A1Q3.

The AC output signal from the collector of A1Q3 is coupled through C1 and R3, where it is chopped to ground by chopper G1, which restores the signal to a DC voltage. Capacitor C3 filters any high-frequency noise generated by chopper G1. The DC signal is then coupled through the low-pass filter formed by R4 and C4 and externally shorted to base B1 of Q1.

Diode CR3 prevents excessive positive signals from damaging polarized capacitor C4 and, in combination with diode CR7, allows fast recovery for Q1 from any overload condition. The high-frequency component of the input signal (blocked from the AC section by the low-pass filter at the input) is coupled through C5 and R9 to Base B2 of Q1. Transistor Q1 forms a differential DC amplifier, whose output is the sum of the amplified signal from the AC amplifier section and the high-frequency components of the unamplified input signal.

The use of a balanced transistor and current balancing resistor R2 in the emitter circuit insures that no signal is present at the output of Q1 under no-signal input conditions. Zener diode CR5 establishes and maintains the DC operating level at the emitter of Q1. Zener diode CR4 in the collector circuit of Q1 aids fast recovery during overload conditions. The summed DC signal at the collector of Q1 is direct-coupled to the base of Darlington configuration transistor Q2, which forms a DC voltage amplifier. Resistor R14 and capacitor C6, between the collector and the base of Q2, provide intergrated degenerative feedback to

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smooth fast-changing DC voltages appearing at the output of A1.

The amplified DC signal at the collector of Q2 is applied through the fast-coupling network formed by C8 and R15 to the base of amplifier Q3. Q3 further amplifies the combined DC signal, which is then applied to the base of driver transistors Q4 and Q5. C7 and R17, between the collector and the base of Q3, provide integrated degenerative feedback to further smooth any fast-changing DC signals. Diodes CR6 and CR8, in the collector circuit of Q3, establish and maintain temperature-compensated DC foward bias at the bases of Q4 and Q5.

Q4 provides drive for Q6 during the positive portion of the output signal, and Q5 provides drive for Q7 during the negative portion of the output signal. Protection from external overload is provided for Q6 and Q7 by current limiting resistors R21, R22, and R24. The DC output is developed at the collector of Q7 and the emitter of Q6. Feedback from the output is applied through R13 and R10 to the B2 base of Q1 to establish overall DC gain and to maintain amplifier stability.

Exercises (665):

1. In the DC amplifier assembly, foldout 28, why is the DC input signal converted to an AC voltage?

2. In foldout 28, how is the AC gain of A1Q1 and A1Q2 established?

3. What effect does chopper G1 (foldout 28) have on the output AC signal of A1Q3?

4. What signals make up the output of Q1 in foldout 28?

5. What is the function of CR6 and CR8 in the collector circuit of Q3 in foldout 28?

6. How is capacitor C4 protected from excessive positive signals (foldout 28)?

7. Why is the DC gain of the first two stages of the AC amplifier very low?

8. What type of feedback is used for Q3?

666. Using a schematic diagram of the power amplifier, trace the integrator shaft assemblies and state the purpose of specified components.

Power Amplifier Assemblies 3A9 and 3A15. Each power amplifier assembly contains two separate power amplifier channels that provide drive voltage for the integrator shaft assembly motors. These are shown in foldout 29. Each power amplifier channel has provisions for amplifying two separate inputs (align and navigate). The align input signal is applied to a preamplifier (used only during ALIGN) and then to the power amplifier. The navigate signal is applied through an impedance attenuation network to the power amplifier. The impedance attenuation network prevents low-level signal voltages from driving the amplifier and thereby producing erratic integrator shaft movement. Since the two channels differ only in the impedance attenuation network configuration, we describe only one channel.

The align input DC signal is applied to limiter diodes A3CR1 and A3CR2 during the ALIGN mode of operation. Diodes A3CR1 and A3CR2 limit the positive and negative portion of the signal to approximately +1.7 VDC and -1.7 VDC. Chopper G1 chops the signal to ground at the junction of A3R3 and A3C2. The DC signal is converted to a 400-Hz square wave by the action of chopper G1 and applied to the base of amplifier transistor A3Q1. Transistors A3Q1 and A3Q2 form a compound-connected AC amplifier. The AC signal at the collector of A3Q2 is direct-coupled to the base of amplifier transistor A3Q3.

Capacitor A3C5 and resistor A3R12, between the collector and the base of A3Q3, provide degenerative feedback to prevent high-frequency oscillation. Zener diode A3CR3 establishes the DC operating level at the emitter of A3Q3. The output signal at the collector of A3Q3 is coupled through A3C7 to the base of A3Q4. Capacitor A3C7 is shunted by zener diode A3CR4, which prevents the signal at the collector of A3Q3 from overdriving A3Q4. Resistors A3R9 and A3R7, between the collector of A3Q4 and the base of A3Q1,

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provide linear feedback to the three AC amplifiers for stability and for reduction of the effect of noise generated by the amplifiers. Capacitor A3C8 bypasses spikes riding on the square wave.

During the ALIGN mode, the output signal from the collector of A3Q4 is connected externally (by energized contacts of A26K15) to the base of Q1. Zener diode A1CR1, in the base circuit of A1, establishes the maximum negative voltage that can be applied to the base of Q1 at approximately -6.2 VDC.

Transistors Q1 and Q2 and transformer T1 operate as a paraphase converter to provide balanced ground signals, 180° out of phase, to drive push-pull output amplifiers. As the positive voltage at the base of Q1 increases, the current in the emitter and collector circuits also increases. As conduction increases in Q1, terminal A of T1 and the junction of R1 and R2, in the emitter circuit, become more positive. This increasing positive voltage is coupled to the emitter of Q2, causing a decrease in conduction through Q2. The decrease in Q2 collector current causes terminal C of T1 to become more positive. The phasing polarity of the T1 secondary voltage is positive at terminal D and negative at terminal F.

Diode CR3, from the base of Q4 to ground, shunts most of the negative voltage present at terminal F of T1 to ground. This prevents a high-negative voltage from completely cutting off Q4 and Q6. The small-negative voltage applied to the base of Q4 causes a decrease in the conduction of Q4 and Q6. The positive voltage at terminal D of T1 causes an increase in the conduction of Q3 and Q5. This results in negative and positive voltage output from the collector of Q5 and the collector of Q6, respectively.

When the signal at the base of Q1 becomes negative, the action of the paraphase converter and the output amplifiers is essentially reversed. Diodes CR4 and CR5 establish the operating level at the base of Q3 and Q4. Transformer T2, between the collectors of Q5 and Q6, provides degenerative feedback to the emitter of Q1 for frequency stability.

In the NAV mode, the DC signal input voltage is applied through impedance attenuation (dead zone) network A1CR3, A1CR4, and A1R9. The dead-zone network prevents low-level signal voltages from driving the amplifier, thus keeping undesired drive voltages from the integrator shaft assembly motors. When a positive voltage (0 to 4 volts) is available, zener diodes A1CR3 and A1CR4 are reverse biased, and produce a high resistance. In this instance, the amplifier does not produce an output because the dead-zone network has a high impedance that attenuates the input voltage.

When the input signal voltage reaches approximately +4.0 VDC, zener diodes A1CR3 and A1CR4 break down, reducing the impedance of the dead-zone network to a low value and allowing the input signal to pass with minimum attentuation. The DC input signal is then chopped to round at a 400-Hz rate by chopper G1, converting the DC input to a 400-Hz square wave. The signal is applied to the base of paraphase converter transistor Q1 during the NAV mode through externally shorted contacts of A26K15. The two out-of-phase signal outputs from paraphase converter transistors Q1 and Q2 are applied to the push-pull output circuit, amplified, and applied to the integrator shaft assembly motors.

Exercises (666):

1. What is the function of A3C5 and A3R12 foldout 29) in the collector-to-base circuit of A3Q3?

2. What is the function of zener diode A1CR1 which is in the base circuit of Q1 in foldout 29?

3. What purpose does transformer T2 (foldout 29) between the collector of Q5 and Q6 serve?

4. How many separate inputs can each amplifier channel accept?

5. Why is degenerative feedback provided to A3Q3?

6. What is the function of the Dead-zone network in the NAVIGATE INPUT (position)?

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7. Refer to foldout 29. What components sets the DC operating level for the emitter of A3Q3?

667. Trace a schematic diagram of the summing amplifier assemblies and state the purpose of specified components.

Summing Amplifier Assemblies 3A6, 3A12, 3A13, and 3A16 Through 3A19. Each summing amplifier consists of two identical modulated carrier DC amplifier channels. Each channel consists of two sections: an AC section (modulated carrier) and a DC section. Locate these in foldout 30. The DC input signal is converted to a 400-Hz square wave by a chopper and amplified by the AC section. AC amplification results in greater amplifier stability for low-level input signals. Greater amplifier stability reduces drift, which has the effect of introducing a spurious signal of the same nature as the signal being amplified. The AC signal is then restored to a DC level and further amplified by the DC section. Since both channels of each summing amplifier are identical, the operation of only one channel will be described in detail.

The DC input signal number one to the assembly is applied through a low-pass filter formed by resistors A1R1 and A1R2 and capacitor A1C1 and chopped to ground potential at the junction of A1R2 and A1C2 by chopper G1.

The signal is applied through A1C2 and A1R3 to the base of Darlington configuration transistor A1Q1. The signal is amplified and direct-coupled to the base of Darlington transistor A1Q2. Feedback from the emitter of A1Q2 through A1R6, to the base of A1Q1 establishes the AC gain of the two transistors. The pulsating DC gain is very low because of the bypass action of capacitor A1C4 in the emitter circuit of A1Q2.

A resistive and capacitive decoupling network in the collector circuit of the two transistors prevents the AC variations from affecting the DC operating supply voltage. The amplified AC signal is direct-coupled from the collector of A1Q2 to the base of Darlington transistor A1Q3. Resistor A1R11 and capacitor C1 establish the AC gain of A1Q3. The AC output signal from the collector of A1Q3 is coupled through C3 and R1 to the DC amplifier section. Chopper G1 restores the signal to a DC voltage at the junction of R1 and R3. Capacitor C5 Filters any high-frequency noise generated by G1. Resistor R3 and Capcitors C7 and C8 form a low-pass filter to produce a DC voltage proportional to the output of the AC section at the base of Q1. Transistors Q1 and Q3 act as low-level DC amplifiers. Diode CR3, from the emitter to the base of Q1, allows fast recovery from any overload condition. The DC signal at the collector of Q1 is coupled through R8 to the base of Q3. The output of Q3 provides the input signals to driver transistors Q5 and Q6. Capacitor C11 from the collector to the base of Q3 provides integrated degenerative feedback to smooth fast-changing DC voltages appearing at the output of Q1.

Transistor Q5 provides drive for Q9 during the positive portion of the output signal, and Q6 provides drive for Q10 during the negative portion of the output signal. Diodes CR1 and CR5, in the collector circuit of Q3, establish and maintain temperature-compensated DC forward bias at the base of Q5.

Protection from external overload is provided for Q9 and Q10 by current limiting resistors R21, R22, R23, and R26. The DC output is developed at the collector of Q10 and the emitter of Q9. Feedback from the output is applied through R14 to the emitter of Q1 to establish overall DC gain and aid in maintaining amplifier stability.

Exercises (667):

1. What is the function of the resistive and capacitive decoupling network in the collector circuit of A1Q1 and A1Q2 in foldout 30?

2. In foldout 30, what is the function of C5?

3. Why is AC amplification used in the summing amplifier assemblies?

4. What is the function of the filter mode up of R3, C7 and C8?. Refer to foldout 30.

5. Refer to foldout 30. How is external overload protection provided for Q9 and Q10?

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668. Trace a schematic diagram of the integrator shaft assembly.

Integrator Shaft Assembly 3A24. The integrator shaft assembly contains four integrator shafts that provide the computed velocity and distance-traveled outputs, the power output transistors for the gimbal servoamplifier outputs, demodulators for longitude and latitude inputs, and synchronizer for the dual-latitude synchro inputs. Assembly 3A24 is shown in sheets 1 and 2 of foldout 31.

Each integrator shaft consists of a motor, a capacitance tachometer switch, and one or more output devices. The outputs are provided by precision potentiometers or synchros that are positioned by the shaft. The shaft is driven by the drive motor, through the necessary gear ratios, to provide correct scaling of the outputs. Functionally, the capacitance tachometer switch is composed of three segments and a wiper arm. One segment is connected to a positive voltage, another segment is connected to a negative voltage, and the third segment provides the output. The wiper arm is connected to an LC network.

As the wiper arm rotates, the capacitor connected to it is charged first positive, then negative; or, depending upon the direction of rotation, first negative, then positive, and then discharged. The discharge occurs when the wiper arm touches the output segment and results in a series of positive or negative pulses. The inductor connected to the wiper arm acts as an arc suppressor. The operation of the individual integrator shafts differs only in the type and number of output devices, so only the latitude integrator shaft is described.

The latitude integrator shaft is continually positioned to present position latitude. During INS alignment, the latitude drive motor control phase is developed from the latitude demodulator output. During NAV mode, control phase voltage is developed from the integral of +Vy. Precision potentiometers, positioned by the latitude shaft, provide the sine, cosine, and tangent functions of latitude required for the gyro torquing circuits.

High- and low-speed control transmitter outputs are applied to control transformers B6 and B7 respectively. (See the bottom center of foldout 31, sheet 1). The output of control transformer B7 is applied to the base of A4Q11 in the synchronizer circuit through A4R19. The output of control transformer B6 is applied through A4R23 to the base of A4Q12. When the signal at the collector of A4Q11 exceeds the breakdown potential of zener diode A4CR3, the low-speed synchro controls the conduction of A4Q13.

As the synchros approach a null, and the collector output of A4Q11 no longer can exceed the breakdown potential of diode A4CR3, transistor A4Q13 is controlled by the high-speed synchro output from the collector of A4Q12. The emitter output of A4Q13 is applied to the emitter of latitude demodulator transistor A5Q14 (upper center of foldout 31, sheet 2). Demodulator reference voltage is applied to the base of A5Q14. The demodulator output is used to set the latitude shaft to the initial-position latitude during INS alignment.

During the NAV mode, the control phase for the latitude motor is computed. When the amplitude of the control phase is sufficient to overcome the motor threshold, latitude drive motor B5 turns the latitude shaft (see the lower left of foldout 31, sheet 1). Note that the latitude shaft drives the wiper arm of S4, R13A, R13B, R17, R18A, R18B, R18C, and the movable contact of S6. Precision potentiometers R13A and B, R18A, B, and C apply sine, cosine, and secant functions of latitude to the gyro torquing circuits. The tangent function of latitude is provided by precision potentiometer R17 (upper left of foldout 31, sheet 2), a precision resistor network, an external summing amplifier, and relay A4K6. The output segment B2 of S4 applies feedback pulses through contacts 5 and 2 of A4K2 to assemblies 3A4 and 3A10, located within the computed section of the navigational computer.

Potentiometer R17 and the resistive network are excited by +Vx or -Vx. Negative or positive Vx is selected by relay A4K4, which is controlled by switch S5. The arm of potentiometer R17 is connected to the external summing amplifier input, and the potentiometer center tap is connected to the summing amplifier output. As the arm is rotated from 0° to 90° latitude, the input resistance to the summing amplifier varies from maximum to minimum while the feedback resistance varies from minimum to maximum. At 70° latitude, a cam on the latitude shaft actuates switch S6, which energizes relay A4K5, and the NO contacts apply +28 VDC to relay A4K6. When relay A4K6 energizes, the summing amplifier closed-loop gain is increased so that the output more closely approximates a tangent curve.

Exercises (668):

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1. During what mode is the latitude drive motor control phase voltage developed from the integral of +Vy (foldout 31)?

2. What signal is used to set the latitude shaft to the initial position latitude during INS alignment?

3. Refer to foldout 31. What relay selects +Vx or -Vx as excitation for potentiometer R17?

4. What input signals are applied to the segments of capacitance tachometer S1?

5. Refer to foldout 31. What is the function of inductor A1L2?

6. How is switch S6 actuated?

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Maintenance

WHEN SOMEONE SAYS that no electronic system or component can run forever, or never need maintenance of repair, they are certainly correct. Some systems are more reliable and do not malfunction as often as others; but sooner or later, all break down and need repair. This is also true for inertial navigation systems. Many items of equipment and maintenance procedures used to check other systems are used with the INS, but there is also a variety of unusual test equipment utilized. In this chapter, we will identify some of these unusual methods and equipment.

8-1. LRU Bench Test

In this section, we will highlight important points or steps utilized in bench testing LRUs of a typical INS. Remember, for a thorough outline of the procedure, refer to the applicable TO.

669. Explain the procedure and equipment used in performing a bench check of the platform, computer, OSDU, or control unit.

Platform. The bench test procedures for the platform include a platform resistance and continuity check, a preparation procedure, and the platform tests.

When handling the platform, use the intended handholds provided beneath the top shock mounts. Air valve intakes or exhaust vents are not reinforced enough to serve as handles. They were designed for the maximum flow of air and take the minimum amount of space necessary for this. Therefore, do not put pressure on them.

Perform the resistance and continuity check to assure correct resistance and continuity of the platform. If these checks are not performed on all no-go platforms prior to testing, damage to the platform test set could result. Normal limits are listed in the TO, and all deviations should be investigated to prevent possible damage to test equipment and/or associated equipment. Careful consideration must be given to multiple parallel circuits where one of the components (if open) has little effect on the resistance of that circuit. Use a platform resistance/continuity check box.

The preparation procedure insures the proper interconnection and operation of the test set, test equipment, and the platform. The platform preparation procedure includes bench test setup, test equipment setup, recorder calibration, test set setup, and test set self-test procedures. For example, before performing the platform tests, the recorder must be accurately calibrated. If the recorder is not calibrated, then platform tests will not be reliable.

The platform tests are outlined in detail in the applicable TO. Remember, no matter how well you feel you know the procedure, always refer to the TO section defining the test being performed.

Computer. The performance of the computer can be checked in a minimum of time by performing the bench test procedures. These procedures provide means of isolating a malfunction to a replaceable assembly. The bench test procedures include a preparation procedure, the computer tests, and a turnoff procedure.

The preparation procedure insures the proper interconnection and operation of the test set, test equipment, and the computer. The computer preparation procedure includes bench test setup, test equipment and test set setup, and test set self-test procedures.

Typical test equipment used to check the computer includes an oscilloscope, integrating

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digital voltmeter, vacuum-tube voltmeter, and an audio signal generator. Capabilities are provided for connecting the test equipment to the front of the test set. If a test requires isolating chassis ground of any or all external test equipment, exercise caution; you could get a big jolt or even be electrocuted by touching such test equipment.

Perform the self-test when the integrity of the test set is suspected. The tests are detailed in the applicable TOs. The test can be performed individually provided the procedures within each test are performed in sequence. If the overall reliability of the computer is in doubt, perform all checks. If a specific section is malfunctioning, perform only checks concerning it. Also, when a subassembly has been replaced, perform checks concerning it.

When all testing has been completed, turn all switches OFF in reverse order unless instructed to do otherwise.

OSDU. The performance of the OSDU can be checked in a minimum of time by performing the bench test procedures. These procedures provide a means of isolating a malfunction to a replaceable assembly. The bench test procedures include a preparation procedure, OSDU tests, and a turnoff procedure.

The preparation procedure insures the proper interconnection and operation of the test set, test equipment, and the OSDU. The OSDU preparation procedure includes bench test setup, test equipment and test setup, and test set self-test procedures.

Only three pieces of test equipment are required to test the OSDU on the test set. These are the integrating digital voltmeter, vacuum-tube voltmeter, and the oscilloscope. As with the computer, capabilities are provided on the front of the test set for connecting the test equipment.

After the tests have been completed, turn off all switches and circuit breakers in reverse order unless instructed to do otherwise. Make sure that all receptacles are covered with protective caps to prevent bent pins and contamination by dirt, grease, or oil.

Control Unit. The performance of the control unit can be checked in a minimum of time by performing the bench test procedures. These procedures provide a means of isolating a malfunction to a replaceable assembly. The bench test procedures for the control unit, as in previous units, include a preparation procedure, the control unit tests, and a turnoff procedure.

Preparation and turnoff procedures are the same as for the computer and OSDU. Test equipment required for testing the control unit on the test set is the integrating digital voltmeter and oscilloscope.

As indicated above, each LRU can be individually checked out on the test set without having to hook up a complete INS. After completing the appropriate test and determining which test passed and which ones failed, troubleshooting will be necessary to correct the malfunction.

Exercises (669):

1. Why must a resistance and continuity check be completed on the platform before performing any platform tests?

2. What device is recommended for performing platform resistance checks in a minimum amount of time?

3. What must be done when the integrity of the test set is suspected?

4. Why must receptacles be covered with protective caps?

8-2. Troubleshooting

To find and repair a malfunction in the INS is not radically different from any other normal electronic repair job. In this section, we will point out important steps to keep in mind while hunting for that troublesome component or malfunction.

670. Given a hypothetical troubleshooting situation in the INS, state what action should be taken to repair an LRU.

Platform. In the TO there is a field platform testing and repair flow diagram that should be used in conjunction with the platform tests. The flow diagram shows where to proceed when a test passes or fails. Recommended

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actions that can be taken to correct or verify a malfunction are shown.

After replacement of the upper gyro, allow the accelerometers time to cool to room temperature (about 30 minutes) before applying electrical power. If the upper gyro is replaced and power is applied while the accelerometers are hot, the heat detector located in the upper gyro will sense the temperature of the cold gyro, thus applying heat to both the gyro and the already hot accelerometers. This may possibly damage the accelerometers.

If you should have to disassemble the platform, disassemble it in an area with better than normal housekeeping. While the platform is disassembled, keep it segregated from excessive dirt and dust generating operations. It is advisable that this area be temperature controlled so that the maximum temperature will not exceed 80° F. The maximum recommended humidity level is 50 percent at 80° F., but no damage is expected unless this environment is steadily violated for weeks. Platform dust covers must be utilized for all unsealed platform maintenance actions, except for replacement of gyros.

For disassembly, assembly, purging, and filling instructions, refer to the TO for detailed instructions.

Computer. When a defective computer is to be repaired, the computer tests will normally be performed in their entirety to determine the operational integrity of all circuits. However, if the operational malfunction symptom is known, time can frequently be saved by referring to tables 8-1 and 8-2 and performing those tests relating to the circuits most likely to have caused the malfunction.

In the event of a malfunction, refer to the computer and control functional diagram and the schematic diagram referenced at the beginning of each test. Test points, in addition to those required for the tests, are shown for use in troubleshooting.

Further isolation is accomplished by removing the suspected assembly and substituting a good assembly. It is assumed that only one failure has occurred at a time. If the substitution fails to correct the malfunction, proceed to the next most likely items on a sequential basis until the failure is corrected.

TABLE 8-1
OPERATIONAL MALFUNCTION SYMPTOMS

Operational Symptom	To Locate Malfunction, Perform Computer Test No.
Latitude, longitude and ground speed in error	1, 2, 3, 4, 15 and 20 thru 29
Latitude indications in error	1, 2, 3, 4, 15, 21, 24, 25 and 27 thru 29
Longitude indications in error	1, 2, 3, 4, 15, 20, 22, 23, 26 and 28
Ground speed indications in error	1, 2, 3, 4, 15, and 20 thru 29
Azimuth displays incorrect	1, 2, 3 and 16
Pitch displays incorrect	1, 2, 3 and 17
Roll displays incorrect	1, 2, 3, 17 and 18
INERTIAL NAV SYS OUT indications abnormal	1, 2, 3, 4, 11 thru 18, 20 and 21
HEAT light indications in error	1, 2, 3 and 4
ALIGN light indications in error	1 thru 15, 16 thru 18, 20 and 21

NOTE: Perform only those tests applicable to the computer part number being tested.

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TABLE 8-2

CONFIDENCE TESTING AFTER ASSEMBLY REPLACEMENT

Item Replaced	Computer Test Number																									
	1	3	3A	4	5	7	8	10	11	12	14	15	16	17	18	19	20	21	22	24	26	27	28	29
3A1	X	X													X									
3A2	X	X		X									X					X						
3A3	X	X												X										
3A4	X	X							X								X		X		X		X	
3A5	X	X						X													X		X	
3A6	X	X															X		X		X		X	
3A7	X	X										X		X										
3A8	X	X			X	X	X	X			X													
3A9	X	X							X												X		X	
3A10	X	X						X												X		X	X	
3A11	X	X						X														X	X	
3A12	X	X						X												X		X	X	
3A13	X	X																					X	X
3A14	X	X			X	X	X	X	X															
3A15	X	X						X												X		X	X	
3A16	X	X															X						X	
3A17	X	X															X	X						
3A18	X	X						X								X	X	X						
3A19	X	X																						
3A20	X	X																						
3A21	X	X																						
3A22	X	X						X								X	X	X	X	X	X	X	X	
3A23	X	X		X	X	X	X	X																
3A24	X	X		X				X					X	X	X	X	X	X	X	X	X	X		X
3A25	X	X																						
Chassis	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Filter	X	X																						
Solenoid	X	X																						
Blower	X	X																						

NOTE: Perform only those tests applicable to the computer part number being tested.

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When any assembly is substituted, perform the computer coincidence tests specified in table 8-2 to determine if the malfunction has been corrected.

When the results of the test indicate that the fault has been corrected, replace the defective assembly and perform the remainder of the computer tests to completely verify the performance of the computer.

Exercises (670):

1. If you replace the upper gyro, why must you wait 30 minutes before applying power to the platform?
2. What is the maximum temperature recommended to disassemble the platform?
3. What is the best method for isolating a malfunction in the computer?
4. Referring to table 8-1, what computer test should be performed if the roll displays are incorrect?
5. How can repair time be reduced during the repair of a computer if the operational malfunction is known?

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6. After a 3A25 power supply assembly has been replaced, what tests should be performed to determine if the malfunction has been corrected?

8-3. Alignment

In the INS, there are several unusual alignment procedures and, in this section, we will discuss the more important ones.

671. State the unusual and important procedures used during alignment and adjustment of the INS.

To align the gyros and accelerometers in the platform, a Sanborn Recorder is required, and accuracy of gyros and accelerometers is determined by the accuracy of the recorder. To insure an accurate alignment, the recorder should have a minimum of 20 minutes warmup time before platform tests will be run. After warmup, the styli must be centered on the chart and individual deflection angles calibrated.

Located on the OSDU are the X-, Y-, and Z-gyro bias potentiometers. Each potentiometer has a calibrated scale that is checked for accuracy during OSDU tests; however, the gyros themselves are in the platform. Gyro bias is not determined by adjusting these potentiometers, but is determined by adjusting a similar dial on the test set during platform tests. Then the dial readings on the test set are transferred to the dials on the OSDU which will accompany that particular platform.

Exercise (671):

1. Do both the platform and OSDU have to be connected simultaneously to the test set to adjust gyro bias? Why?

2. What determines accuracy of the gyros and accelerometers during alignment?

3. After warmup of the Sanborn Recorder, what must be done to the styli?

4. How is platform gyro bias determined?

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CHAPTER 9

Free Azimuth Inertial Navigation System

THE NORTH SEEKING inertial system installed on tactical fighter aircraft performs aircraft and performs its mission well. However, there are some limitations to the system, such as inaccuracies over long range navigation and operation in polar regions. It is also limited in the number of waypoints or targets that can be loaded at one time. The target or waypoint must be updated manually at each mission leg change. The free azimuth inertial navigation system overcomes most of these problems. In this and the next chapter,s we will look at the free azimuth inertial navigation system and its characteristics. We will call it the Carousel INS because our typical free azimuth inertial navigation system also uses a carouseling effect. This will be explained later. Information on this chapter is extracted in part from material released to the Government by the Delco Electronics Division of General Motors.

9-1. General Description and Function of the System

The Carousel INS is a lightweight, automatic, self-contained navigation set, capable of providing extremely accurate worldwide navigation capability on a self-contained basis. That is, the system requires no external references, such as ground based radio or radar installation, nor does it rely on visual, radio, or radar "observations" from the aircraft. Besides doing primary navigation functions, the Carousel INS also may be a source for enroute steering to the autopilot, for display of flight navigation data, and for attitude information. for the aircraft.

The fundamental principle involved is the ability of the system to sense and measure aircraft acceleration. Once aircraft acceleration has been measured, it can be converted to velocity and distance traveled from a point of origin to keep track of aircraft velocity (track and ground speed) and position (latitude and longitude). Insertion of the desired flight plan provides the system with that information necessary to compute flight plan related navigation information, such as desired track, cross-track distance, track angle error, and so forth.

The Carousel INS consists of four basic units. The heart of the Carousel INS is the *navigation unit* (NU), containing the inertial reference unit, associated electronics, and the computer. The *mode selection unit* (MSU) allows the operator to select the mode of operation. The *control/display unit* (CDU) serves as a communication link between the operator and the system computer. The *battery unit* (BU) serves as a backup power source to keep the system operational after loss of primary power. Each of these units will be discussed in detail later.

672. Identify the sections of the navigation unit and state the function of its components.

The Navigation Unit. The navigation unit (fig. 9-1) contains the major elements of the Carousel INS: the inertial reference unit (IRU); inertial reference unit electronics (IRUE), including power supplied and thermal control elements; and the digital computer unit (DCU). First, we will discuss the inertial reference unit.

Inertial Reference Unit. The inertial reference unit (IRU) uses a four-gimbal assembly to support a platform which is stabilized at a reference attitude. It contains the electromechanical devices for stabilizing the platform and producing signals proportional to changes in aircraft attitude and velocity. The signals enable the digital computer to provide complete navigational data for display and aircraft use. The electromechanical devices are gyros, accelerometers, motors, synchros, and resolvers. Figure 9-2 shows a simplified model of the IRU showing the gimbals in a level condition, the platform aligned and erected for flight. Note that the platform assembly consists of two platforms: X–Y and Z. The Z platform's major assemblies are a dummy accelerometer and a single degree of freedom gyro with its input axis oriented in the vertical. A synchronous motor and gear train, also mounted on the Z platform, drives the X–Y platform about the vertical at one revolution per minute. The major subassemblies on the X–Y platform include two single axis gyros and two accelerometers, with their relative orientations depicted in the lower right corner of figure 9-2.

During the navigation mode of operation, two platforms are maintained in the horizontal, as illustrated, through the action of the X–Y platform-mounted gyroscope and accelerometers, gimbal torque motors (mounted on the outer-roll, pitch, and inner-roll gimbal axes), and the DCU. The gyroscope mounted on the Z platform is used as an azimuth reference for the platforms. As a result, when the aircraft changes attitude or heading, the combined functions of gyros, accelerometers, and computer force a change in the relative gimbal orientation, thus maintaining the desired

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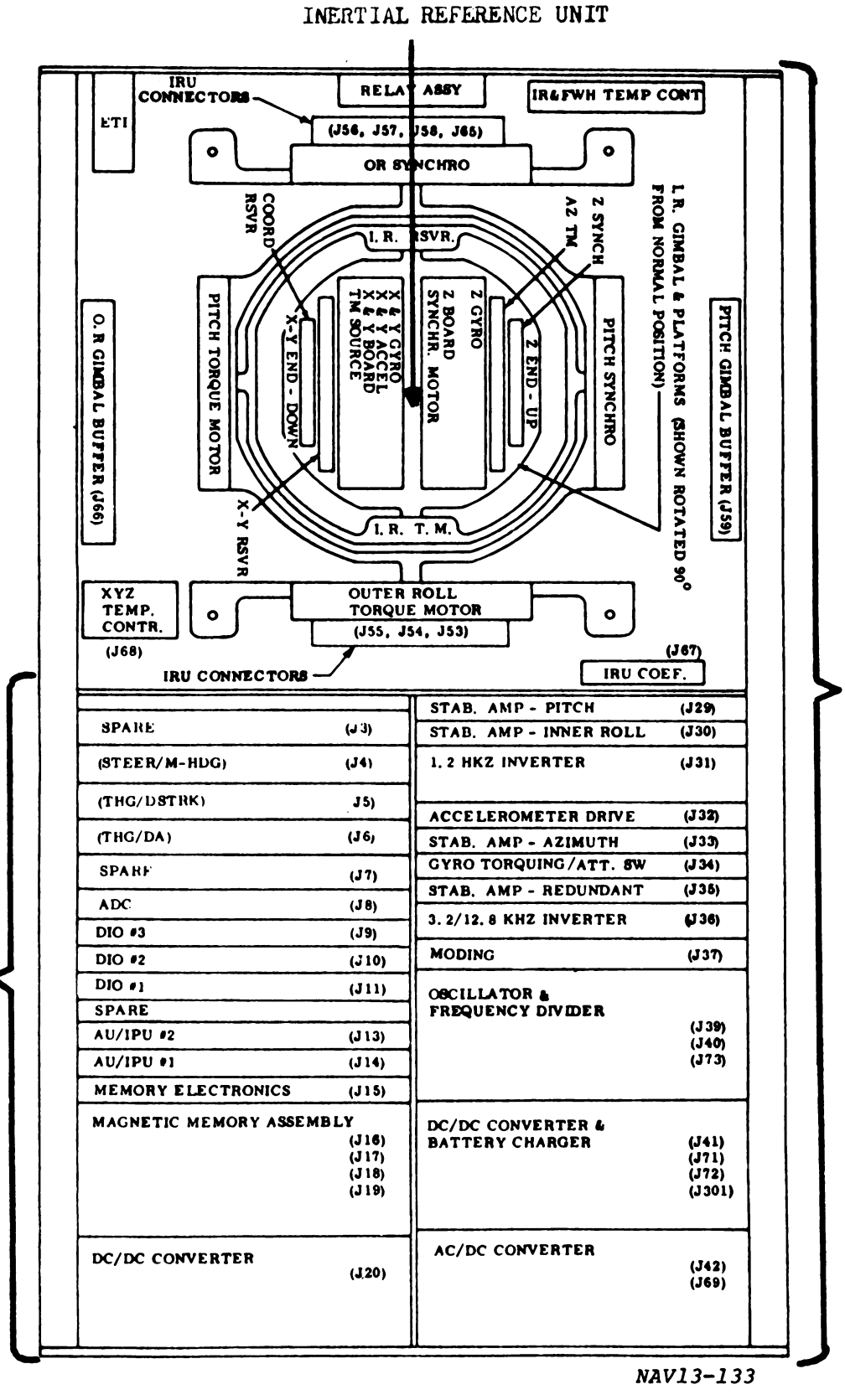

Figure 9–1. Inertial navigation unit-top view. (Reproduced with permission of the Delco Electronics Division of General Motors)

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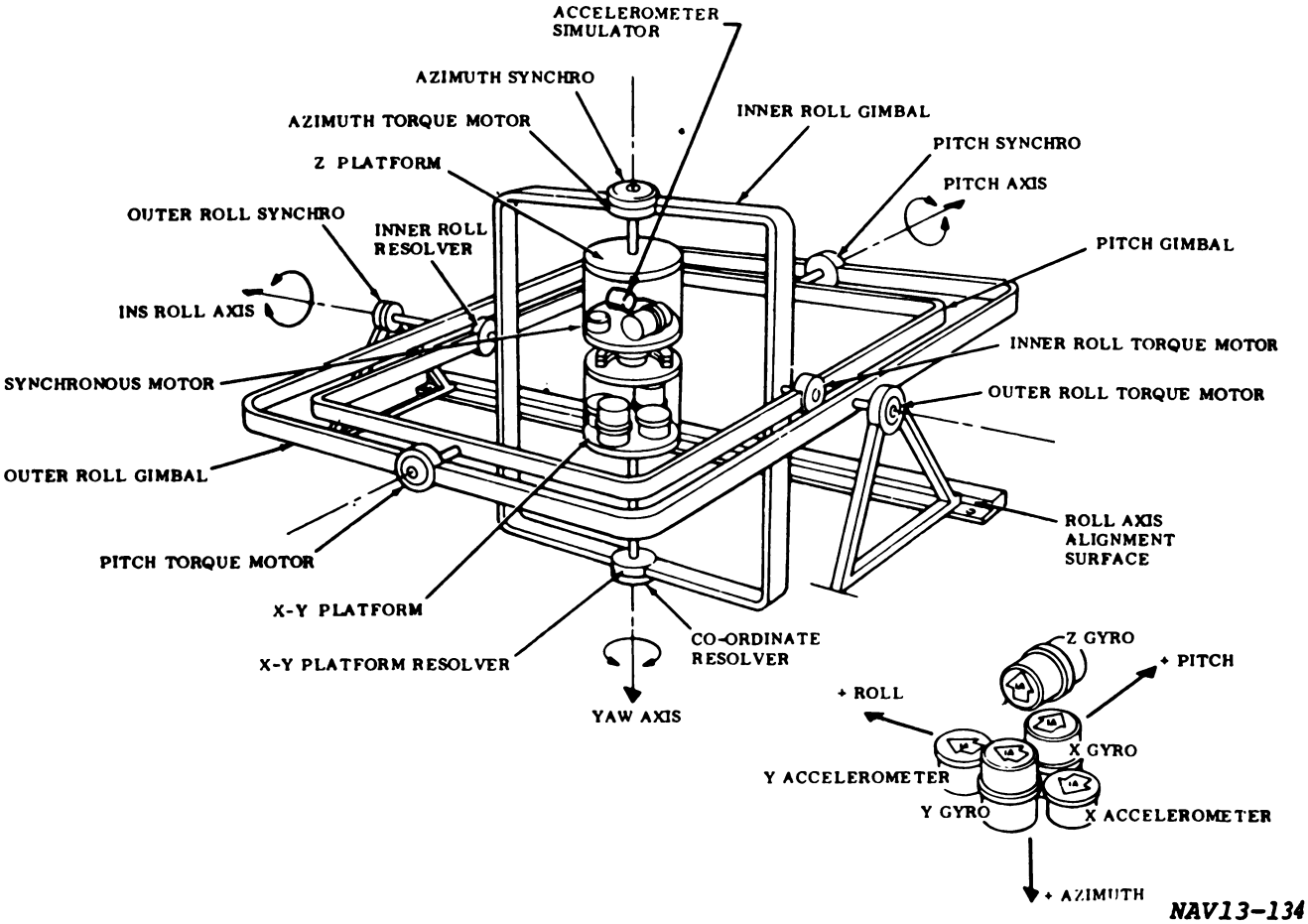

Figure 9–2. Simulated Carousel INS platform. (Reproduced with permission of the Delco Electronics Division of General Motors).

horizontal and azimuth platform reference. Aircraft attitude and platform heading is then directly available as outputs from synchros mounted on the outer-roll, pitch, and azimuth gimbal axis.

Inertial Reference Unit Electronics. The inertial reference unit electronics (fig. 9-1) contains all the power supplies (except for the computer) and electronics for the stabilization loops, accelerometer loops, gyro torquing, moding, and temperature control. The inertial reference unit electronics are composed of printed circuit cards divided by function to simplify maintenance.

Exercises (672):

1. Name the electromechanical devices located in the inertial reference unit.

2. How many platforms are contained in the platform assembly? Name them.

3. How is the input axis of the Z platform oriented?

673. Identify and specify the purpose of the blocks of the digital computer unit, and cite details related to this unit's operation.

Digital Computer Unit. The digital computer unit (DCU) is a binary-serial device which continuously performs many computations at a high rate of speed. The computer consists of 10 plug-in circuit cards (7 input/output, 2 arithmetic/instruction processing, and a memory electronics), a plug-in magnetic memory, and its own power supply. Functionally, the computer does all of the following:

- Solves mechanization equations required for great circle navigation.
- Provides great circle enroute steering signals.
- Provides navigation data to the Control/Display Unit and aircraft interface equipment.

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- Provides system status information to the control/display unit and aircraft interface equipment.
- Provides gyro torquing control (signals to keep the platform earth referenced).
- Monitors its own operation and that of other system hardware.
- Solves mechanization equations for calibration of inertial instruments during alignment.

The computer is composed of the following functional blocks: timing, memory, arithmetic unit/instruction processing unit, and input/output unit. Each of these blocks serves a specific function and can be further broken down into operational blocks (fig. 9-3). Let's look briefly at each block.

Timing is critical to proper operation. Information must be read out of and written into memory in a given sequence. If an arithmetic operation is to be performed, the two operands must be present and shifted at the proper time. These actions depend on a control timing device This timing device also generates low frequency timing pulses to synchronize computer operation with the slower operating input or output devices.

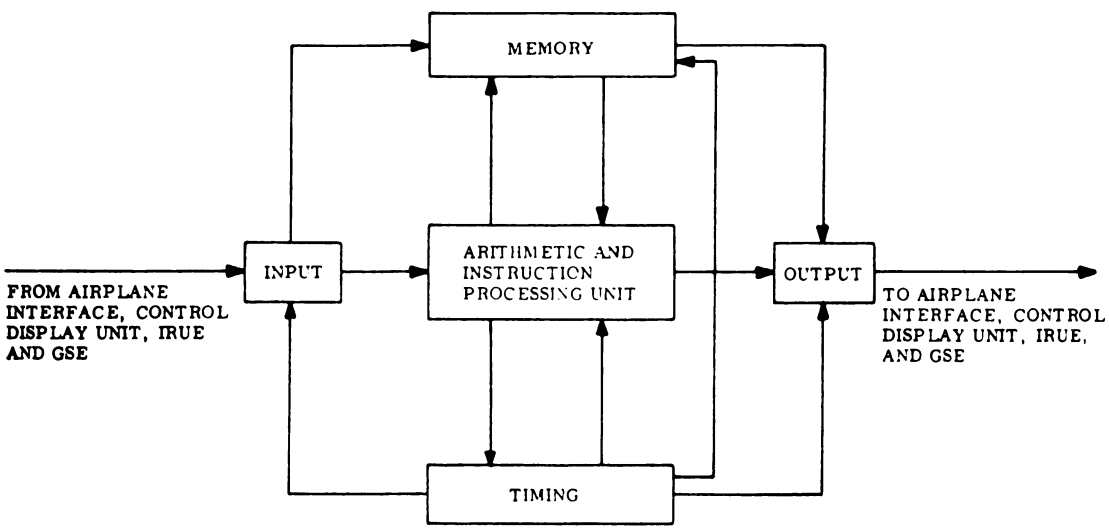
The memory of the computer stores instructions, constants, and the results of calculations. The memory stores data from computations performed in the arithmetic unit/instruction processing unit or data that is processed through the input/output unit. The computer can address any cell in memory and transfer the information to either the arithmetic/instruction processing unit or to the input/output unit. Instruction words are stored in one memory cell, and data words, which are twice as long, are stored in two consecutive memory cells.

The arithmetic unit/instruction processing unit of the computer decodes the instructions read from memory, selects the next instruction or data to be read out, keeps track of which instruction is to be read next, modifies a sequence of operations and perform the operations commanded by the program.

The input/output unit is the interface between the information processing portion of the computer and the inertial reference unit, control/display unit, ground support equipment, and other aircraft systems. Input and output to the computer are in discrete, binary, binary coded decimal, or analog form. Input and output discrete from the navigation unit or ground support equipment, accelerometer input data, and digital-to-synchro outputs are handled through the arithmetic unit/instruction processing unit. All other data interfaces with the computer memory directly and is handled through the automatic input/output processor in the input/output unit.

Exercises (673):

1. Name the four functional blocks of the digital computer unit.



*GSE - GROUND SUPPORT EQUIPMENT

Figure 9–3. Computer functional flow. (Reproduced with permission of the Delco Electronics Division of General Motors)

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2. Which of the four units insure that two operands for an arithmetic operation will be present and shifted at the proper time?

3. Compare the length of an instruction word to a data word.

4. What are the four types of inputs and outputs to the computer?

674. State the characteristics of timing signals in the digital computer unit.

Timing Source. Orderly computer operations are is accomplished by control signals generated from a timing source. See figures 9-4 and 9-5 for the timing breakdown from the computer. Basic timing for the computer is derived from a frequency standard located in the IRUE. A 6.144 MHz sine wave is fed to the computer as the basic timing frequency. Circuits in the computer shape the sine wave to a square wave and divide it by two to form the basic clock rate of 3.072 MHz. The basic clock rate is further divided to form pulses that control input and output functions such as accelerometer input processing. The control pulses synchronize input/output functions with computer operations.

The clock rate is also sent to a bit-time counter or shift register which has 20 outputs: BT01 to BT20. The outputs are combined or used separately to shift data or instructions within the computer. Basic bit rate, BT20, and an instruction code are fed to a phase generator whose 20-bit length outputs determine what will be done with data within the arithmetic/instruction processing unit. There are three outputs of the phase generator. Output C0 is considered the instruction procedure phase. During the first 8 bits, the 12-bit instruction is shifted out of memory in parallel and during the last 12 bits the instruction is shifted, serially, to an instruction decoder. During the first 8 bits of C1, the first half-word of data is shifted out of or into memory in parallel and in the last 12 bits, first half-word data is shifted serially into or out of registers in the arithmetic/instruction processing unit. (The instruction and data words will be explained later.) Output C2 is identical to C1 except data is the last half-word data.

The sequences of processing is dependent on the instruction to be performed. Long instructions such as multiply and divide require a C0 to procure the instruction from memory and then C1 and C2 are

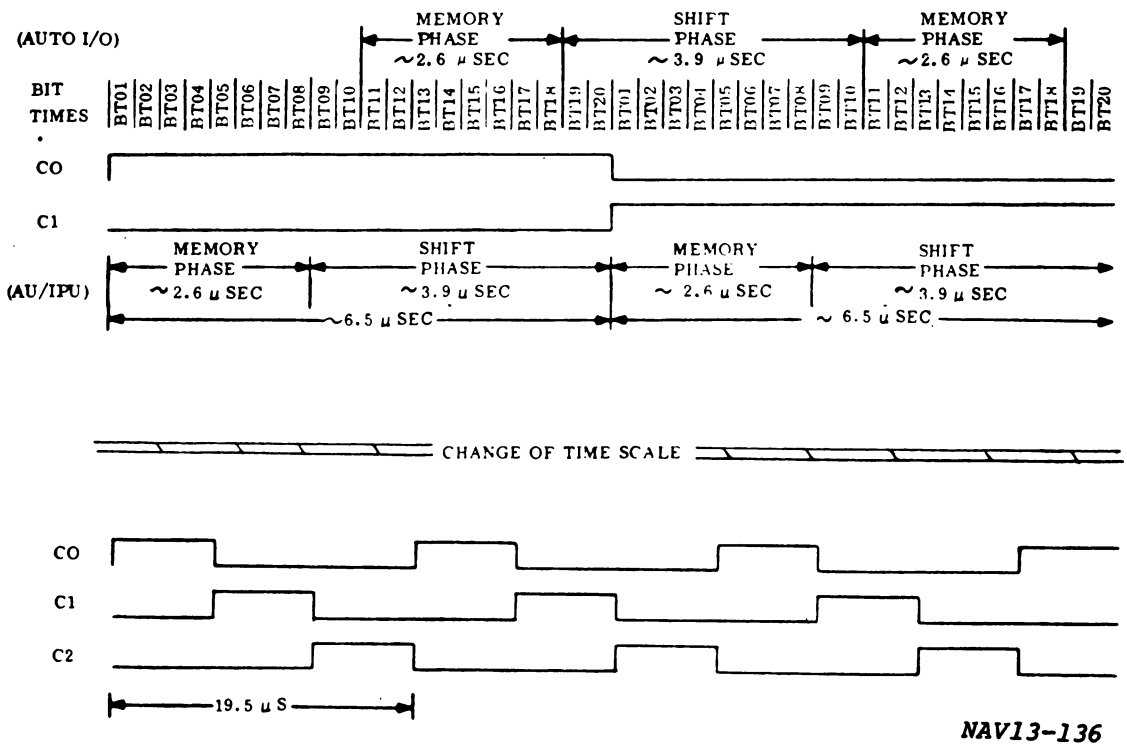
(AUTO I/O)
MEMORY PHASE ~2.6 μ SEC
SHIFT PHASE ~3.9 μ SEC
MEMORY PHASE ~2.6 μ SEC
BIT TIMES
BT01 BT02 BT03 BT04 BT05 BT06 BT07 BT08 BT09 BT10 BT11 BT12 BT13 BT14 BT15 BT16 BT17 BT18 BT19 BT20 BT01 BT02 BT03 BT04 BT05 BT06 BT07 BT08 BT09 BT10 BT11 BT12 BT13 BT14 BT15 BT16 BT17 BT18 BT19 BT20
C0
C1
(AU/IPU)
MEMORY PHASE ~2.6 μ SEC
SHIFT PHASE ~3.9 μ SEC
~6.5 μ SEC
MEMORY PHASE ~ 2.6 μ SEC
SHIFT PHASE ~3.9 μ SEC
~ 6.5 μ SEC
CHANGE OF TIME SCALE
C0
C1
C2
19.5 μ S
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Figure 9-4. Computer basic timing. (Reproduced with permission of the Delco Electronics Division of General Motors)

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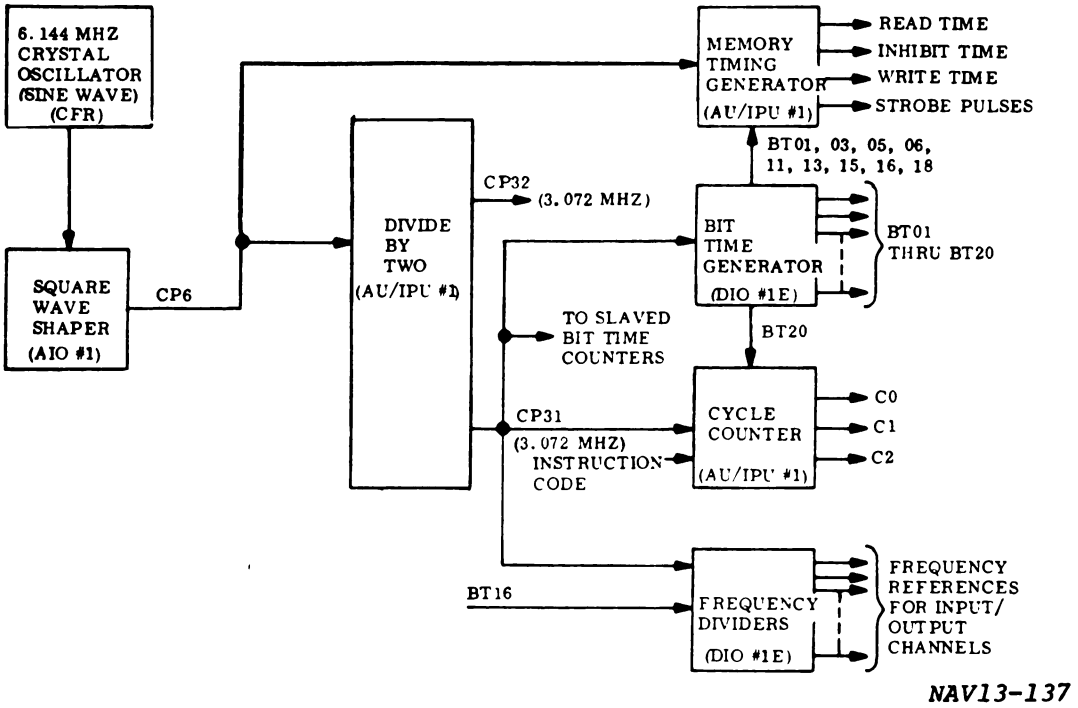

Figure 9–5. Carousel INS computer timing generator block diagram. (Reproduced with permission of the Delco Electronics Division of General Motors)

alternately repeated until the instruction is complete. A single add would require a C0, C1, and C2 and a single transfer operation would require only a C0 phase.

Input/Output Timing Generator. The input/output unit (IOU) timing generator provides pulses that will synchronize computer operation with input data or output data with the equipment that it interfaces with. Several inputs or outputs are supplied to one IOU circuit. The signals necessary to time share the circuit are provided in the timing generator. A 20-Hz interrupt signal is also produced that forces the computer to enter a routine no matter where it is in its program. This routine will update data such as accelerometer inputs and gyroscope torquing outputs.

Memory Timing. Special timing circuits are required to read information out of or into the memory cores. The timing circuits produce read, write, inhibit, and enable sense amplifier pulses for memory operation. These timing pulses will be covered in the next objective.

Exercises (674):

1. Where is the frequency standard located from which the basic timing for the computer is derived?

2. What is the basic timing frequency?

3. Name the three outputs of the phase generator.

4. Which of the phase outputs is required to execute a transfer operation?

5. Which circuit allows the IOU to time share?

675. Identify the size, location, and purpose of the memory in the Carousel INS.

Memory. The memory consists of a core array (which stores instructions and data) and associated electronics for writing binary information into or reading binary information out of the memory core.

The memory has a storage capacity of 8192 words, each 13 bits in length (12 data bits and 1 parity bit). See Table 9-1 for computer characteristics. The memory's storage capacity is functionally divided into two groups. One group is used for instructions, transfer table, and constants that will not be changed during computer operation. The other group is used as temporary storage for data and instructions during the computer operation. The number and locations of words in each group varies with the specific program. However, certain word

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TABLE 9–1
COMPUTER CHARACTERISTICS

	Item
Computer Type:	Serial (data processing) Parallel (memory interface)
Data Word:	24 bits (including sign), binary
Instruction Word:	12 bits
Memory Type:	Lithium-ferrite toroidal core, coincident-current mode
Memory Size:	8192 words (12 bits plus parity)
Speed:	
Memory Access:	2.6 microseconds
Memory Access and Shift:	6.5 microseconds for 12-bit word
Add/Subtract:	19.5 microseconds for 51,282/seconds or 3,076,920/minutes
Multiply:	32.5 to 175.5 microseconds Average = 101.4 microseconds
Divide:	332 microseconds or 3012/seconds or 180,720/minutes
I/O:	19.5 microseconds
I/O Capability:	Example:
Pulse inputs	Velocity envelopes
Digital data inputs and outputs (Binary or BCD)	INS2 or Doppler computer/SKE/TACAN
Discrete signal inputs and outputs	External program discretes
DC inputs and outputs	XTK output
Synchro inputs and outputs	FDC/AFCS information
Self-check inputs	Program timing check signal

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locations and regions of the memory have been allocated for special functions. For example, the first 777_8 words of memory are known as "directly addressable memory"; the first eight words of memory have special usage in return-from-subroutine and return-from-interrupt instructions; locations 2000_8—2377_8 are used as a transfer table for the transfer-to-subroutine instructions; location 3000_8 is used as the start location (all programs must begin with the instruction at this location); and location 2400_8 is reserved for interrupt purposes.

The memory core array is a conventional four-wire coincident current, toroidal core system. The four wires which thread each core are X-axis drive, Y-axis drive, inhibit, and sense. The memory contains 13 mats, each of which contains 8192 cores (64 x 128) and represents one bit of the 13-bit memory word. The X-axis and Y-axis drive lines thread the 13 mats so as to select one of the 8192 cores in each mat (word select). The drive lines are bidirectional with current direction dependent upon whether the mode is a read or write. Each sense line threads all the cores in a single mat (bit sense). The sense line outputs are bipolar. Each inhibit line is unidirectional and threads all the cores in a single mat.

Figure 9-6 shows the organization of the memory system, consisting of the core storage array and the circuits directly engaged in storage and retrieval. The address and data registers, parity logic, and memory timing are located in the arithmetic unit/instruction processing unit.

The memory address to be read from or written into memory is formed either in the memory address register when the address is generated or is the new address register when the address is a function of the automatic input/output unit. Switching logic will input the appropriate register contents to the address decoding logic. The address decoding logic decodes the address and selects the appropriate X and Y drive lines in memory. Assuming a read operation is erasable memory, the timing generator will issue a read time pulse (RT). One of the sink switches is selected (by the address) and current flows through the stack of cores to the selected source switch. This current has a regulated amplitude which is controlled by the current regulator. The selected memory cores are switched and produce outputs from the sense amplifiers where logic ones were stored but no outputs where logic zeros were stored. The sense amplifier outputs, directed by switching logic, set the memory register or the new data register for the positions which were logic ones. The appropriate register now contains the data or instruction word which was read out.

To put the word back into memory, the timing generator issues inhibit and write time pulses (IT and WT). A different set of sink and source switches are selected and current is fed back through the same X and

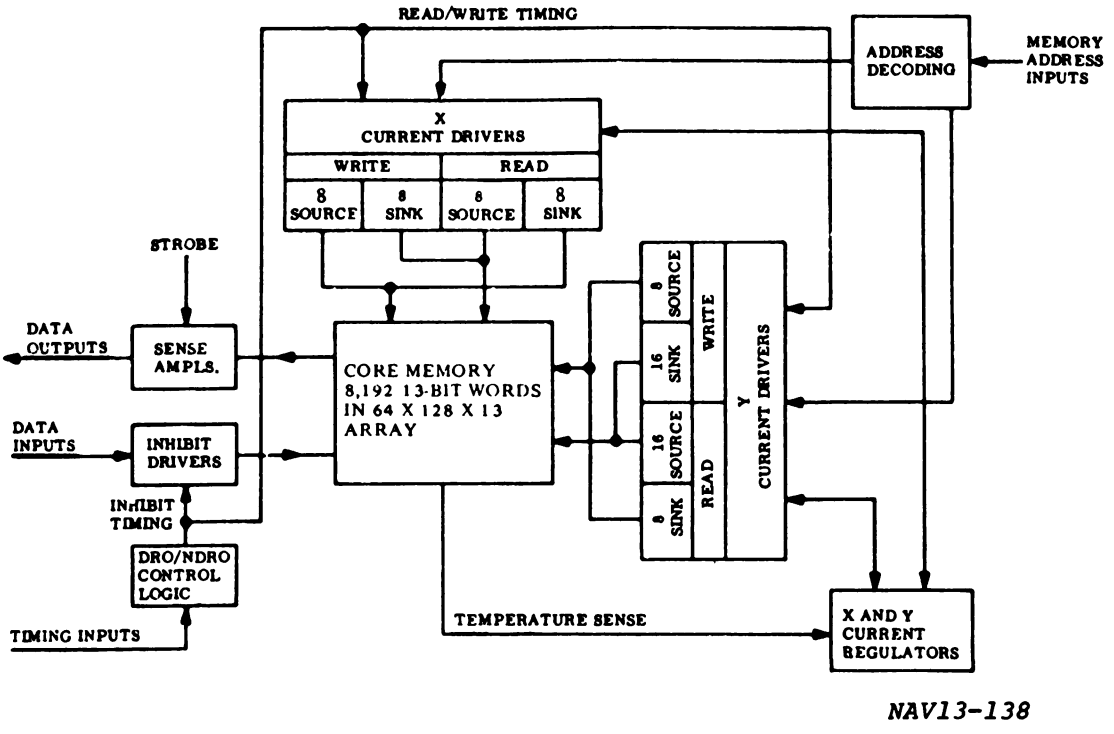

Figure 9–6. Memory block diagram. (Reproduced with permission of the Delco Electronics Division of General Motors)

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Y drive lines, but in a direction opposite to that used for read. The core will be switched back unless an inhibit current is fed through the core plane for that particular bit position, i.e., inhibit currents are provided whenever a logic zero is to be written into the memory.

To write a word into memory, the address is selected as above for read, and the word contained in the memory register or the new data register is written into memory as described in the above paragraph.

Memory timing consists of several flip-flop and gated circuits which produce the timing signals for memory (fig. 9-7). These timing signals are produced during the computer basic cycle, bit time 1 through 20. They allow the arithmetic unit/instruction processor unit to address memory during the memory phase and the automatic input/output unit to address memory during the shift phase of the basic cycle.

At bit time one (BT1), a read time (RT) signal is generated to enable the X and Y selection circuits to be addressed; this signal stays high for 3-bit times. During BT3 a strobe signal (STR), approximately 100 nanoseconds wide, enables the output of the sense amplifier to be read. The strobe signal is required because of noise on the sense line which could provide an erroneous readout. Therefore, the sense amplifier output is strobed to sample the output at the time when the sense signal-to-noise ratio is optimum. This same operation is repeated during BT11 through BT13 for addressing by the automatic input-output unit. At BT6, a write time (WT) signal is generated to enable the X and Y selection circuits to be addressed; this signal also stays high for 3 bit times. To inhibit the X 1/2I current in these cores where zeros are to be written, an inhibit signal (IT) is generated at BT5 and stays high through BT9. This write operation is also repeated in the shift phase with the WT signal generated at BT16 and the IT signal at BT15.

Information in memory is protected during computer turn-on and turn-off. Refer to figure 9-8. When a command is given to turn on the computer DC-to-DC converter, a computer power turn-on circuit is enabled. A small delay in this circuit allows the converter outputs to stabilize prior to issuing a discrete (PND) that will energize a circuit in memory to turn on the current regulators. After a 12-millisecond delay that allows the X and Y current regulators to stabilize, the PND discrete also causes another circuit in memory to issue the memory ready (MER) discrete. The MER discrete is then fed to the bit time generator to enable its outputs and start computer operation.

When the command is given to turn the computer off, the PND discrete through the computer turn-off circuit drops immediately. The dropping of PND starts to turn off the current regulators. The current, however, does not start to decrease until approximately 10 microseconds after PND drops. The fall of PND and the end of the word cycle in process (C0, C1, and C2), which occurs within 6.5 milliseconds, cause MER to fall

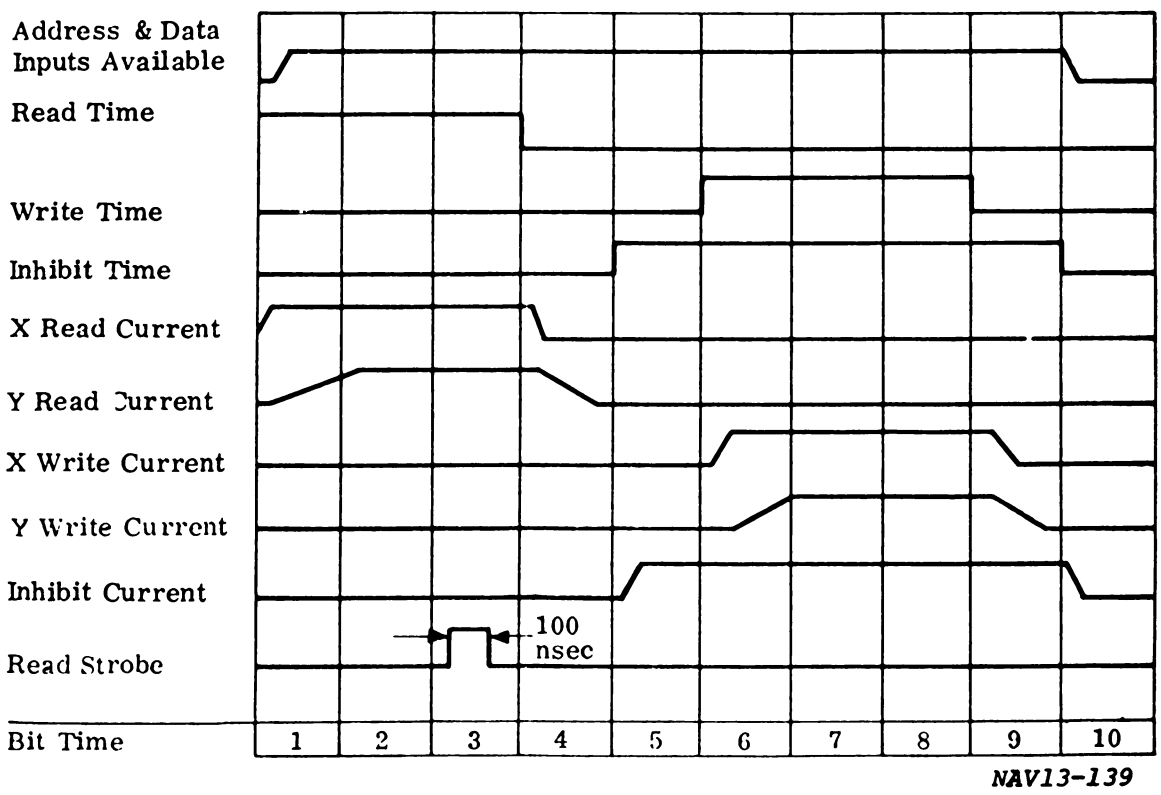

Figure 9–7. Memory timing diagram. (Reproduced with permission of the Delco Electronics Division of General Motors)

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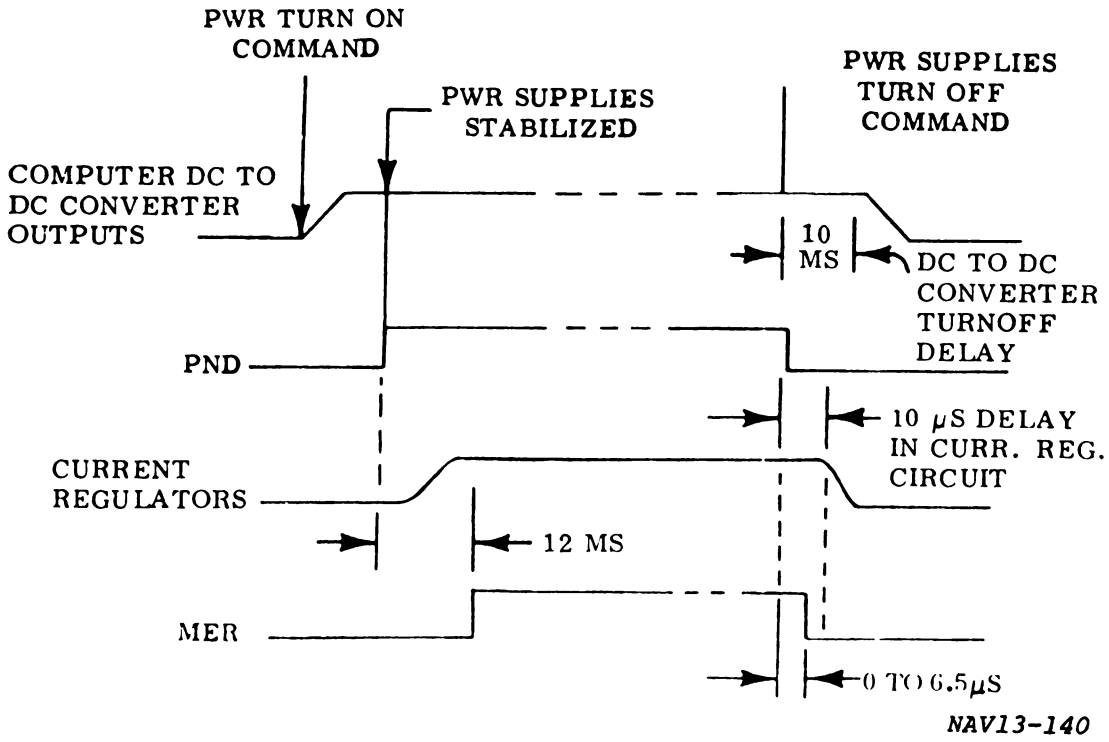

Figure 9–8. Memory start shutdown sequence. (Reproduced with permission of the Delco Electronics Division of General Motors)

and disable the master bit time counter. In this way, if a read/write or memory cycle is in progress at the fall of PND, it is completed, but no further memory accesses are permitted. The DC-to-DC converter has built-in turn-off delay of approximately 10 milliseconds. The delay allows the current regulators to turn off and the computer to complete a memory cycle before the output voltages of the converter go to zero.

Exercises (675):

1. What size storage capacity does the Carousel INS have in memory?

2. What memory location is used as the start location?

3. Name the four wires which thread each core of memory.

4. What is the purpose of the turn-on delay circuits?

5. What is the purpose of the turn-off delay circuits?

676. State the characteristics of an instruction word and a data word.

The Carousel INS computer uses memory cells capable of storing 12 bits of actual information. Two basic types of information are stored: *instruction words* and *data words*.

Instruction Words. The program, which controls the operation of the computer, is composed of a set of instructions stored in memory. Each instruction is composed of 12 bits of information and is stored in one memory cell. The coded instruction is read from memory at the appropriate time under control of the arithmetic unit/instruction processing unit (AU/IPU) and the corresponding hardware action is initiated. Four general categories of instructions exist to accomplish: load, store, arithmetic, and logic; shift; transfer; and input/output functions.

The instruction word which is 12 bits in length will tell the computer what to do and where to obtain or store information. Since it must accomplish two functions, it is divided into two parts: the *operand* code, which identifies what is to be done, and the *address* code, which defines one of the following:

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a. The memory address from which information is to be obtained or into which information is to be stored.

b. The address of an input or output channel.

c. The number of shifts to be performed.

The most significant digits (MSD) are reserved for the Operand Code Field and the least significant digits (LSD) for the Address Code Field. The number of digits in each is determined by the instructions to be performed.

Instructions may be designated as EVEN-coded or ODD-coded, according to whether the location in which they are stored is even or odd.

Data Words. Data words are 24 bits in length and, therefore, each requires two memory cells for storage. The least significant half (bits 1 through 12) of each data word is stored in a memory cell with an even-numbered address. The most significant half (bits 13 through 24) is stored in the cell with the next highest odd address. Constants, required by the computer in solving alignment and navigation problems, and the computer's arithmetic answers, are examples of data words which are stored as 23 magnitude bits and one sign bit. The most significant bit (bit 24) is the sign bit. A logic zero as the sign bit indicates that the 23 magnitude bits form a positive binary number. A logic one as the sign bit indicates a negative number stored as the 23 magnitude bits and, further, that the negative number is stored in its twos complement form.

Discrete conditions, external and internal to the computer, which must be known by the computer, are stored as bits in a type of data word called a discrete word. Each discrete function is assigned a bit position in a discrete word and is set to a logic one or zero in accordance with the status of the discrete. To determine the status of an individual discrete condition, the computer interrogates the appropriate bit in the discrete word.

Discrete words which are 24 bits in length contain information regarding some action or event that has taken place external to the computer's processing device. This information grouped into a word is called an input discrete word. If some action or events have taken place in the computer's processing device that must be sent to the computer's output interface, this information is grouped in a word called an output discrete word. The "1's and 0's" in the various digit positions do not represent numbers or data; instead they represent actions or events.

Alignment or navigation data in the computer consists of 24 bits. Twenty-three bits are for magnitude and one is reserved for the sign bit. The most significant digit is the sign bit position.

Each memory location will store 13 bits of information. Twelve bits in the location is either an instruction or one-half of a data or discrete word. The 13th bit represents the odd parity bit for the 12 bits of information shared in the memory location. The parity bit appears *only in memory and the logic that generates and checks parity*.

The least significant half (LSH) (12 bits) of a data or discrete word is *always* stored in an *even* memory location and the most significant half (MSH) is *always* stored in the adjacent higher *odd* location, i.e., if the LSH is stored in memory location 16, then the MSH is stored in 17.

An instruction only 12 bits long can be stored in either an even or an odd location.

Exercises (676):

1. Which type word controls the operation of the computer?

2. How many bits compose an instruction word?

3. Name the two parts of the instruction word.

4. What determines whether the instruction word is EVEN-coded or ODD-coded?

5. How may bits compose a data word?

6. Which bit of the data word determines whether the word is positive or negative?

677. State the purpose of the parts of the AU/IDP.

Arithmetic Unit/Instruction Processing Unit (AU/IPD). This unit is the information processing center of the computer. All equations associated with system alignment, navigation, and data displays are performed based on the data and instructions stored in memory. The AU/IPU, under instruction control, performs self-checks on its own operation, makes reasonableness checks on its input data, performs malfunction diagnostic tests, checks for flight data from the control display unit (C/DU), and sends digital data to output registers for use with the inertial reference unit, C/DU, and other parts of the aircraft.

The AU/IPU basically consists of two sections, the instruction processing unit (IPU) and the arithmetic unit (AU). The IPU decodes the present instructions to find out what operation must be done and contains the circuitry that forms the memory address of either the data required to do the operation or the next instruction. The AU is used to form a communication link between certain input/output data and memory, and contains the

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circuitry to perform various arithmetic operations on data.

Exercises (677):

1. Which portion of the AU/IPU performs calculations on data?

2. Which section forms the memory address of the next instruction?

3. Name the source of flight data for the AU/IPU.

678. State the function of the input/output unit in the computer.

Input/Output. The input/output (I/O) circuits provide the basic communications between the information processing portions of the computer and the IRU, CDU, MSU, and ground support equipment. These circuits and their associated logic perform two functions: converting information (they convert information into a form usable by the computer and into a form usable to the equipment it interfaces with) and matching the computer's speed of operation (3.072 MHz rate) to the much slower rate of the information input and output.

The Carousel INS computer's input/output section is divided basically into two areas. It contains input/output channels that place their information in or take it out of memory via a programmed instruction, i.e., input information is put in the AU/IPU's A register with a computer instruction and then it is stored in memory; or output information is taken out of memory and placed in the A register, and then through a program instruction, the A register contents are shifted to the output channel. These input/output channels comprise what is termed the programmed input/output section.

The remaining input/output channels comprise what is called the automatic input/output channels. These input/output channels do *not* store or receive memory information through the AU/IPU's A register, but rather contain the necessary logic to form the memory address in which the channel information is to be taken out of or put in to. The automatic input/output channels require information access memory when the AU/IPU does not use memory, i.e., while the AU/IPU is shifting data.

Since input/output data associated with the auto I/O channels is asynchronous, access to memory is controlled by logic termed priority (gateman) logic. This logic receives a channel generated service request signal which requests access to memory to do a store or load function on its data. The request is processed in the priority logic and at the right time a service enable is issued. When the channel receives the service enable, it is allowed to use memory. Only one service enable signal can be present at any one time. Several service requests, however, can exist at the same time.

The input/output section of the computer is physically located on seven circuit cards of five types. They are divided into analog and digital card types. The cards are designated as follows:

Analog	
ADC	One card
ACO	Three identical cards
Digital	
DIO#1E	One card
DIO#2E	One card
DIO#3E	One card

Exercises (678):

1. Name the two functions of the input/output section.

2. Name the two areas of the input/output section.

3. Input/output access to memory is controlled by what kind of logic?

679. State the purpose of and identify the functions of the control and display unit, mode selection unit, and battery unit.

Control and Display Unit (CDU). This unit serves as the communication link between the pilot and the system computer. The pilot can read all pertinent navigation data in decimal form. The CDU is also used to insert flight plan data, make track selection, and monitor system operation. The CDU contains a power supply, logic circuits, controls, and indicators. The control and indicators are used to insert information into the computer and to display information contained within the computer. The logic circuits transform inserted data into digital form (binary-coded decimal) which, in turn, are transformed into visual numerical display. The CDU also contains indicators which indicate the operating status of the navigation unit (fig. 9-9). The left-hand and right-hand displays of the CDU are composed of lamps which form numbers, decimal points, degree symbols, left and right directions, and latitude and longitude directions. Primary selection of data for display is made with the 10-position (waypoint) selector, a TEST switch, and a HOLD key when used in conjunction with the data selector. Data to be loaded into the computer is first loaded into the data display by operating the keyboard.

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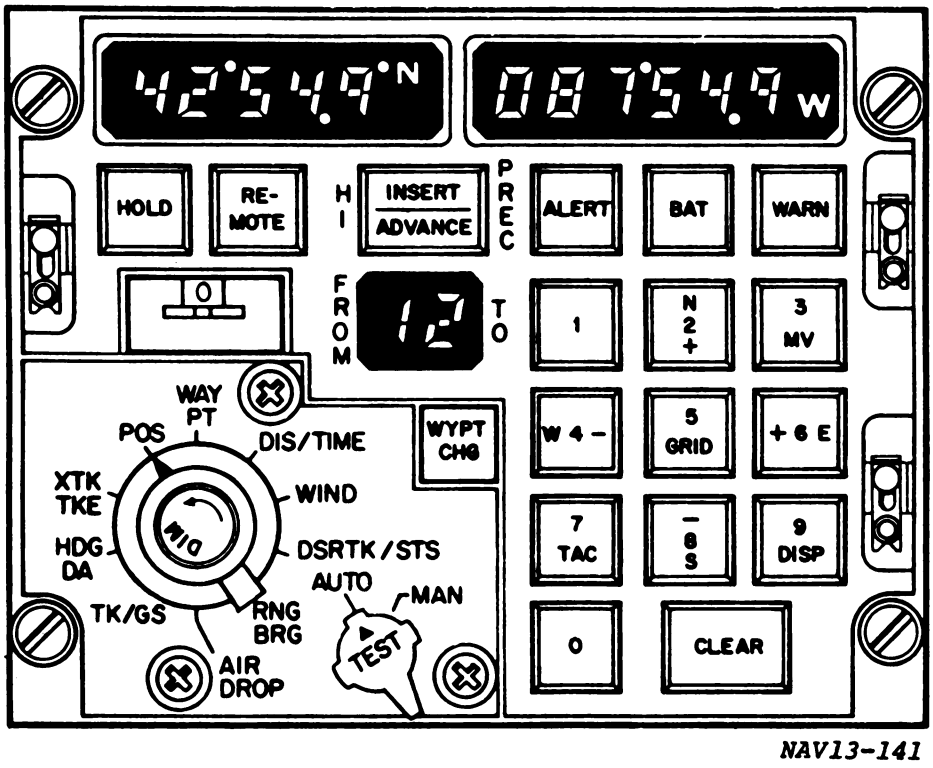

Figure 9–9. INS control display unit.

Display of the loaded data allows visual verification before inserting the data into the computer. Pressing the INSERT key inserts the displayed data into the computer memory, after which the computer resumes its normal control of the displays. CDU displays will be discussed in a later objective.

Mode Selector Unit. The mode selector unit (fig. 9-10) contains a mode select switch and two indicators mounted on the front panel. The mode selector has five positions: OFF, STBY, ALIGN, NAV, and ATT. These positions are used to control operating modes of the INS. The STBY and ALIGN positions are used only during ground operation. The NAV position is used for normal INS operation to provide navigation and attitude data. The ATT position is used to provide only attitude signals from the INS. The mode selector has two mechanical stops which prevent inadvertent switching out of the navigation mode of operation with the resultant loss of INS alignment. The mode selector must be pulled to cross the mechanical stops. One mechanical stop is between the STBY and ALIGN and the NAV and ATT positions.

The two lamps indicate operating status. The BAT lamp (red) lights if the battery unit is not charged enough to sustain INS operation while the INS is operating on battery unit power. Automatic shutdown of the INS is indicated when the BAT lamp lights. The READY NAV lamp (green) lights when the mode selector is in the ALIGN position and the INS has completed the alignment. If the mode selector is advanced to NAV before the READY NAV lamp lights, the INS will automatically sequence to the navigation mode when the desired degree of alignment is attained and the READY NAV lamp will not light. Both lamps can be tested when the mode selector is at any position other than OFF by pressing the TEST switch on the control and display unit. The front panel lettering illumination is controlled by a cabin lighting control.

Battery Unit. The battery unit contains 19 nickel-cadmium cells connected in series to furnish nominal 24 VDC. A 20-ampere circuit breaker on the front of the battery unit protects it from excessive current flow if a short circuit develops.

The battery unit is a 24-VDC, 15.0-ampere-hour battery capable of providing 30 minutes of power for INS operation when fully charged. Its purpose is to provide auxiliary power for INS operation when the 115V, 400-Hz primary input power is interrupted or falls below the required voltage. *Power from the battery unit is used momentarily to initiate INS operation at turn-on and for a 12.8-second test period during automatic INS alignment.*

The battery charger in the navigation unit automatically charges the battery when the INS is operating on 115V 400-Hz power. The battery charger senses battery voltage through the battery sense line. A 50-milliampere trickle charge is applied to the battery unit whenever the INS is turned on. In addition, the

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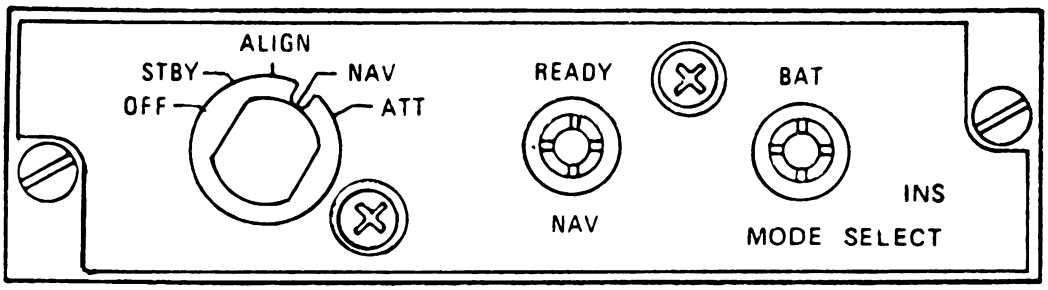

Figure 9–10. Mode selector unit.

battery unit is charged at a constant 2-ampere rate whenever the battery voltage drops below 24 VDC. The 2-ampere charger automatically shuts off when the battery voltage reaches 29.0 VDC.

Exercises (679):

1. Which unit is used to insert flight plan data into the Carousel INS?

2. Which position on the mode selector unit will allow the INS to provide only attitude signals?

3. When fully charged, how long will the battery unit insure voltage for INS operation?

9-2. Theory of Operation

The Carousel INS is typical of modern inertial systems being installed in Air Force aircraft. The system provides extremely accurate navigation information without the need of external input or ground stations of any kind. This section contains the operating principles of the Carousel INS and how it relates to a conventional inertial system. The fundamental concept of mechanization which involves a unique method of suppressing the effects of inertial instrument errors is included. In previous chapters we studied in-depth, the north-slaved inertial navigation system. We found that this system works very well until we approach the polar region (latitude greater than 80°). In these regions the system requires excessive torquing rates to maintain the azimuth aligned to true north which produce azimuth errors. The Carousel INS (a free azimuth inertial navigation system) largely eliminates these errors.

680. Identify the advantages and operational characteristics of the free azimuth inertial system.

Free Azimuth Inertial System. In some inertial navigation systems the problem of excessive azimuth gyroscope torquing is eliminated by not torquing the azimuth gyroscope at all, resulting in the platform being inertially referenced about the local vertical axis. This type of system, called a free-azimuth system, is operational at all latitudes. In such systems, the input axes of the horizontal gyro move about the vertical axis of the platform (free to move in azimuth in relation to local north and east) and are not always pointed north and east. The direction and velocity of the movement of the horizontal gyros' input axes depend on the aircraft's latitude and velocity (an aircraft flying east or west directly over the equator would experience no relative azimuth movement of the horizontal gyro input axes) and do not represent a problem as long as the system is constantly aware of its orientation with respect to true north.

The Carousel INS is essentially a free-azimuth system enhanced by the incorporation of a unique feature which involves rotation of the horizontal inertial instruments (two gyroscopes and two accelerometers) about the local vertical axis. The entire set of horizontal instruments is rotated as a single rigid unit at a 1 rpm rate with respect to the vertical (azimuth) instruments (thus the name Carousel INS). The primary advantage of this carouseling effect is the resultant modulation of the unknown errors related to the sensitive axes of the horizontal instruments. This modulation of the errors minimizes their effect on total system performances. System advantages obtained as a result of the carouseling effect include:

- Complete, automatic instrument calibration.
- Improved alignment accuracy.
- Reduced alignment time.
- Confirmation of system alignment accuracy.
- Suppression of the effects of horizontal errors on flight accuracy.

Next we will see how the Carousel INS overcomes the effects of instrument errors.

Exercises (680):

1. Which inertial navigation system is operational at all latitudes?

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2. Which of the instrument sets rotates about the local vertical axis in the Carousel INS?

3. State the rate of rotation in the Carousel INS.

4. What determines the direction of movement of the horizontal gyro input axes?

681. Identify inertial instrument errors and their effects.

The Perfect System. The horizontally oriented gyros operate with the stabilization servoloops, accelerometers, accelerometer loops, and computer to keep the platform level with the earth as the earth rotates in space and as the aircraft travels over the earth. The azimuth gyroscope and associated stabilization servoloop maintain the platform azimuth orientation in a known inertial position. With precisely aligned, error-free gyros and accelerometers and an accurate knowledge of scale factors, the platform could be kept level by torquing the horizontal gyros about their precessional (output) axes in accordance with velocity information provided by the accelerometers. The total torque applied to the horizontal gyros would be indicative of the total aircraft travel about the spherical earth and the effect of earth rate acting on each gyroscope in accordance with the present aircraft position. The platform would thereby provide a known coordinate frame referenced to earth coordinates from which aircraft attitude, direction, and rate of travel could be measured.

Gyros. In practice, gyros are subject to three principal types of errors which affect their ability to measure the angular travel of the platform: uncompensated drift, torquer scale factor instability, and misalignment of their input axes. Uncompensated gyroscope drift is caused by electrical or mechanical torques which exist in the gyroscope independent of any applied precession torques. As an example of the order of mechanical stability that would be required to reduce drift errors to a level not requiring compensation in navigation applications, a shift in wheel position of less than 10^{-6} is sufficient, in a typical inertial navigation gyro, to cause a 20-nautical-mile navigation error over a 10-hour flight. Torque scale factor error results from an inexact knowledge of the control torque actually applied to the gyroscope to torque it about its precessional axis and occurs largely due to imperfect regulation of the torquing current. Scale factor uncertainty causes an error in computed platform rotation which is proportional to the rotation. Imperfect alignment of a gyroscope input axis causes a gyroscope to sense a small part of the angular rate occurring about another axis; the result appears as a drift of the misaligned gyroscope proportional to the actual platform movement about the other axis sensed by the misaligned gyro. Uncompensated gyroscope errors cause an undesirable gyroscope output which, when processed through the stabilization servoloops, results in a repositioning of the gimbals and the platform to a new, undesired, and unknown orientation. Velocity and position computations are, therefore, inaccurate in proportion to these gyroscope errors.

Accelerometers. Accelerometers are subject to errors which are analogous to gyro errors, although their effects on navigation performance are generally less critical. The principal accelerometer errors are null shift, scale factor, and misalignment errors. Accelerometer null shift affects navigation performance by causing the platform to be positioned out of the desired level orientation. The resulting platform movement is sensed by the gyros and indicated erroneously as distance traveled, but this effect in itself is small and limited. Shift of the platform levelness, however, causes a change in the alignment of the azimuth gyroscope input axis relative to the local vertical, which introduces a misalignment drift into the azimuth gyro. Accelerometer misalignment relative to the horizontal plane has the same effect as shifting the level attitude of the platform and is thus equivalent to null shift in its effect upon navigation. Accelerometer misalignment within the horizontal plane and accelerometer scale factor errors produce maneuver-sensitive errors that persist in the form of 84-minute oscillations in indicated vertical and indicated velocity. Because of the 84-minute period of oscillation, these accelerometer errors have a relatively small effect upon total navigation accuracy. Furthermore, they may be controlled to acceptable levels by straightforward techniques of instrument design and mechanical installation.

Exercises (681):

1. Name three types of gyro errors.

2. What causes uncompensated gyro drift?

3. What will the gyro sense due to the imperfect misalignment of the gyro input axis?

4. Are accelerometer errors generally less critical or more critical than than gyro errors?

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5. What error will accelerometer null shift cause?

682. Describe how the Carousel INS modulates instrument errors.

Carousel Effect. The rotating instrument cluster technique involves rotating the horizontal instrument (X and Y gyros, and X and Y accelerometers) rapidly about the local vertical. The mounting of these instruments is such that their sensitive axes remain in the local horizontal plane. The implementation of this technique provides a 1 r/min constant drive between the two portions of a split platform (fig. 9-11.) The top portion (Z platform) serves as a mount for the X and Y instruments. Since Carousel INS uses a free-azimuth navigation concept (no torquing applied to the azimuth gyro), the azimuth stabilization loop maintains the Z platform inertially stationary. With respect to earth, then, the horizontal instruments rotate at 1 r/min plus or minus the effective rotation of the inertially stable Z platform.

Instrument errors. Inertial instrument errors may be divided into two categories in accordance with how platform rotation affects the impact of the errors on navigation—those errors which remain fixed relative to the rotating instrument cluster and *are* thereby modulated relative to earth coordinates, and those which are basically oriented to earth coordinates regardless of platform rotation and *are not* modulated. The effect of platform rotation on instrument errors can be illustrated in terms of gyroscope drift, which is potentially the most serious of the instrument errors. The navigation effects of a particular instrument error may be assessed most directly by examining components of the error in earth-fixed coordinates.

In a north-slaved platform where the gyroscope input axes are maintained in the north and east directions (fig. 9-12, one gyroscope continuously senses rotation about one axis of the earth. For example, rotation about the east horizontal axis is sensed by the X gyro. If the X gyroscope drifts, the east axis platform angular error and, consequently, the error in computed latitude will increase as a function of time.

If the platform is rotated about its vertical axis (fig. 9-13), the gyroscope drift will remain along the gyroscope input axis and thus the direction of the drift axis will rotate with the platform. As a consequence, the effective drift about the earth's east axis will be reversed when the platform has rotated through 180° and will vary sinusoidally at intermediate platform angles.

Reducing errors. The result of the sinusoidally varying drift about the east earth axis is an angular error which also varies sinusoidally. The horizontal gyroscope drifts then produce only small (modulated at rotation rate) position errors in the geographic reference frame. In a conventional free-azimuth system, the gyro orientation rotates slowly relative to the earth so that a small amount of drift modulation is obtained, but not enough to significantly reduce the impact of drift errors. At the 1 r/min azimuth rotation rate employed in Carousel INS, a horizontal gyroscope drift of 0.03

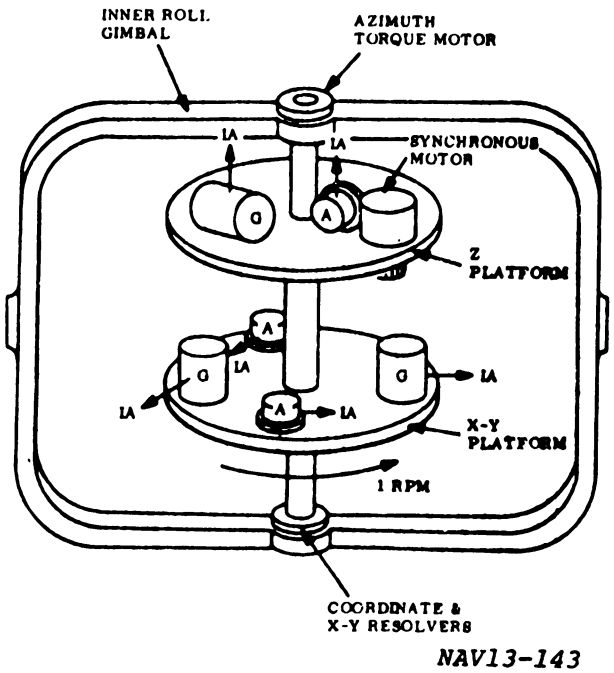

Figure 9–11. Simplified Carousel INS platform.

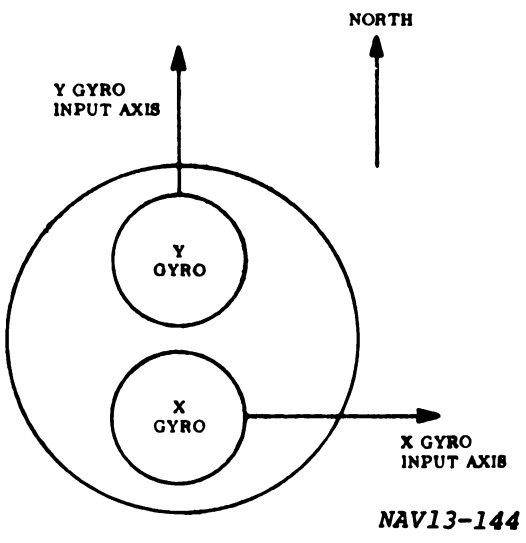

Figure 9–12. North-slaved X and Y input axes.

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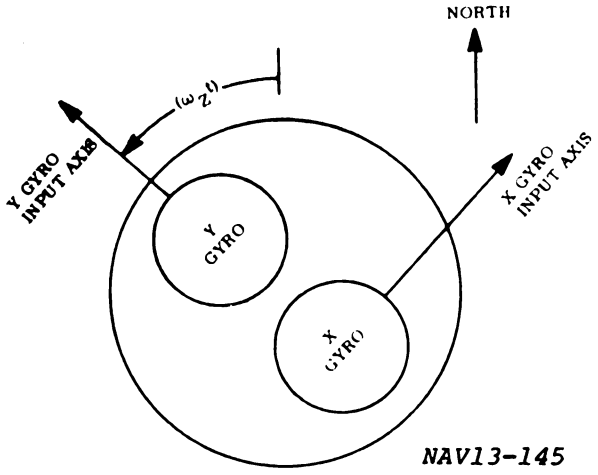

Figure 9–13. Rotated X and Y input axes. (Reproduced with permission of the Delco Electronics Division of General Motors)

degree/hour (which represents the maximum allowable drift for a nonrated platform) produces a platform tilt of only 0.3 arc-second (equivalent to a 30-foot position error). Increasing the drift tolerance by a factor of 100 would leave the effect upon navigation accuracy still completely negligible. If reduction of instrument error effects during navigation were the only consideration, a much lower rotation rate could be used. Alignment benefits, rather than navigation accuracy, govern the choice of rotation rate.

The effect of platform azimuth rotation upon the other instrument errors can be evaluated in a manner similar to that used for gyro drift. The effect of instrument errors on Carousel INS accuracy in comparison to free-azimuth system accuracy is summarized in table 9-2. As indicated by the table, use of the rotating instrument cluster technique confines instrument alignment sensitivity to a single axis for each of the four horizontal instruments.

The dominant remaining errors are initial platform heading errors, azimuth gyroscope drift, and horizontal torquer scale factor. Due to the unique error-modulation characteristics of the Carousel INS, platform heading error is discernible during normal alignment and can, therefore, be compensated for prior to each flight. In addition, by extending the alignment time slightly beyond that required for normal gyrocompassing, calibration factors compensating for the current azimuth gyroscope drift characteristics and for horizontal gyroscope torquer scale factor can be determined.

Alignment. During ground alignment, certain characteristics of a conventional north-slaved inertial navigation system preclude both adequate determination of platform heading and adequate instrument calibration in a single-step process. The self-alignment process may be conventionally thought of as a phase of operation in which external data is available to act upon certain system output variables by virtue of the stationary nature of the vehicle. For example, the aircraft velocity relative to the earth is known to be zero. It follows that any deviation from zero of ground speed output is an indication of an inertial platform orientation error or an uncompensated error source internal to the inertial reference system. Thus, a platform heading error

TABLE 9–2
EFFECT OF INSTRUMENT ERRORS ON SYSTEM ACCURACY

Instrument Error Source	*Effect of Free Azimuth System Accuracy*	*Effect on Carousel IV-E System Accuracy*
Horizontal Gyroscopes	High	None
Drift	High	None
Misalignment (vertical component)	None	None
Misalignment (horizontal component)	Moderate	Moderate
Torquer Scale-Factor	Moderate	Moderate
Azimuth Gyroscopes		
Drift	High	High
Misalignment (two horizontal components)	Moderate	None
Torquer Scale Factor	None	None
Horizontal Accelerometers		
Null Shift	Moderate	None
Misalignment (vertical component)	Moderate	None
Misalignment (horizontal component)	Low	Low
Scale Factor	Low	Low

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corresponds to an incorrect orientation of the horizontal gyros about the vertical axis. In a conventional north-slaved system, this misorientation of the east gyroscope leads to a platform tilt about the east axis since the east gyroscope is receiving a torquing command that is adequate to keep the platform level only if that gyroscope is truly pointing east. As a result of this tilt, the north accelerometer senses a component of the gravity vector and delivers a corresponding output sign, which is integrated to form a finite north velocity. In a typical damped vertical-seeking loop, this north velocity error will be a constant for a constant heading error and may be used to correct the heading error. Unfortunately, in the conventional system, an east gyroscope bias drift produces precisely the same type of north velocity error, and the first limitation of such a system became evident; there is no way of separating east gyroscope bias drift from heading error or of calibrating the east gyroscope drift short of a two-stage (east-west) alignment process. Thus, at a latitude of 45°, an east gyroscope bias drift of 0.01° per hour causes a heading error of about 3 arc-minutes at the termination of an alignment process. Both errors exist in the system at takeoff. It is also impossible to calibrate torquer scale factor errors that may exist in the east gyro, since the ideal torquing rate of this gyroscope is zero and, thus, no stimulus is available for the torquer calibration.

Similarly, the existence of a north gyroscope drift will lead to an east velocity output signal which may be used for applying a correcting torque. Again, in a conventional system, confusion occurs because a north gyroscope torquer scale factor error produces the same result as a north gyroscope drift, and the two conditions are not amendable to individual calibration in a single-stage alignment process. Complete calibration of the gyroscope drifts and torquer scale factor errors in a north-slaved system requires gyrocompassing in four different orientations.

This situation is prevented in the Carousel INS where the horizontal (X and Y) gyros are subject to a precisely known, constant, rapid rotation relative to the gyrographic frame. Bias drift errors associated with these gyros generate sinusoidal errors, of precisely definable frequency, in north and east output velocities. These easily may be subjected to digital filtering of theoretically infinite rejection at the rotation frequency, leaving the lower frequency error characteristics of the velocity outputs open to effective observation and interpretation. Thus, a residual constant value of north velocity is definitely attributable to a platform heading error. A ramp in that quantity indicates the existence of an azimuth gyroscope bias drift, and a constant value of east velocity output is singularly characteristic of horizontal gyroscope torquer scale factor errors. It can be shown that the east velocity output is directly representative of the composite gyroscope torquer scale factor error, and also that error propagation of a Carousel INS in flight is governed by this composite quantity. Its calibration during ground alignment is, therefore, definitely attainable and is sufficient to prevent performance degradation during flight due to gyroscope torquer scale factor repeatability errors. Thus, a Carousel INS is capable of accurate heading determination and complete calibration in a rapid, single-step ground alignment process.

Exercises (682):

1. With respect to earth, how does the horizontal instrument set rotate?

2. Which stabilization loop maintains the Z platform inertially stationary?

3. Name the two categories of inertial instrument errors.

4. What effect does the platform rotation have on effective gyroscope drift?

5. What governs the choice of rotation rates in the Carousel INS?

6. When aligning on the ground, what does a ground speed other than zero indicate to the INS computer?

7. How many steps are required for complete calibration and accurate heading determination?

683. Identify the switch positions and the display indications of the mode selector unit (MSU).

We have seen how errors are mostly eliminated in the Carousel INS using the carouseling effect. They are effectively canceled during alignment and kept to a minimum during operation. Now let's look at displayed outputs of the system.

Mode Selector Unit (MSU). This unit consists of an illuminated front panel, a system mode of operation selector, a ready navigation indicator, and a battery malfunction indicator (fig 9-10). The MSU provides control signals to the moding logic in the navigation unit. These signals condition the logic within the navigation unit to perform the various functions associated with each mode of system operation. (These

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are covered in more covered in more detail in Chapter 10.)

The mode selector is a five-position rotary switch for selecting the following modes of operation: OFF, STBY (standby), ALIGN, NAV (navigation), and ATT (attitude). The switch incorporates a pull-to-turn safety feature to prevent destroying system alignment when switching between STBY and ALIGN mode and NAV and ATT mode.

The READY NAV indicator (green) lights only during the ALIGN mode when the system is automatically aligned to the desired system accuracy.

The BAT indicator (red) lights if the battery unit is not charged enough to sustain system operation when 115V, 400-Hz primer power is removed.

Exercises (683):

1. Name the five positions of the mode selector switch.

2. What is indicated by a lighted READY NAV light?

3. What does the BAT light indicate when lighted?

684. Identify the outputs associated with each position of the data selection on the control and display unit (CDU).

Control and Display Unit. The control and display unit (CDU) serves as the communication link between the operator and the system computer. All pertinent data is read out in decimal form. The CDU also contains indicators which indicate the operating status of the navigation unit. The left and right hand displays of the CDU are composed of lamps which form numbers, decimal points, degree symbols, left and right directions, and latitude and longitude directions. The operator selects data for display with the 10-position data selector (fig. 9-14). In the following paragraphs we will take a look at what data is available to the operator through the data selector.

Output Data Available. Navigation information determined by the INS is defined in the following paragraphs. The relationships between this information and the earth's surface are provided in figure 9-14.

With the data selector set to hDG/DA we have displayed true Heading and drift angle. True heading is

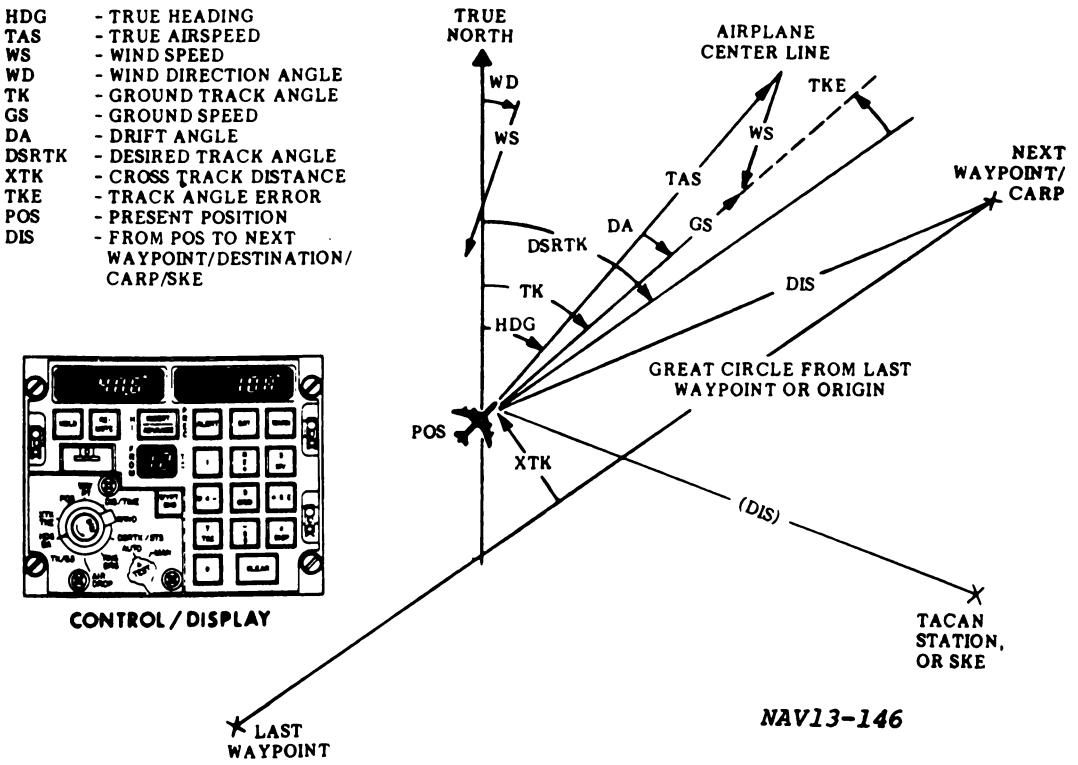

Figure 9–14. Navigation data relationships.

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the clockwise angle from true north to the airplane centerline. Drift angle is the angle between the airplane centerline and ground track or the angular difference between true heading and track angle. Drift angle is right when ground track is greater than true heading and left when ground track is less than true heading.

Now position the data selector to XTK/TKE. Here we have cross-track distance, which is the perpendicular distance in nautical miles from the desired track to the airplane's present position. Cross-track distance is left when the present position is left of desired track and right when present position is right. Track angle error (TKE) is the angle between the airplane track and desired track. It is left when actual track angle is less than desired track angle and vice versa.

In the POS position, we have the actual latitude and longitude coordinate of the point on the earth's surface directly below the airplane at any given time. In the WAYPT position we load waypoints into the computer.

Next, DIS/TIME, distance (DIS) can be one of these distances:

- The great circle distance from airplane present position to desired waypoint.
- The great circle distance between any two waypoints.
- The great circle distance from present position to any TACAN station.
- The great circle distance from present position to computed air release point (CARP).

Time (TIME) is the time in minutes, based on the present ground speed to fly the great circle course of one of the following:

- Present position to the next waypoint.
- Present position to any waypoint.
- Any two waypoints.
- Present position to CARP.

The WIND position will indicate wind speed (WS), which is the velocity of the wind with respect to the earth's surface, and wind direction (WD), which is the clockwise angle from true north to the direction from which the wind is coming.

Next, go to the DStRK/STS position. Desired Track angle (DSTRK) is the clockwise angle from true north to the great circle path between any two points on earth. The magnitude of this angle varies, depending on the point of the great circle at which it is measured. System status (STS) is used for the system testing to indicate malfunctions which have occurred during flight.

The RNG/BRG position indicates the range and bearing between the IP (initial point), PI (point of impact), and TE (trailing edge) when in air drop mode.

The AIR DROP position is used only for air drop data display.

The TK/GS position indicates track angle (TK) which is the clockwise angle from true north to a line which defines the direction the airplane is moving over the earth's surface, and ground speed (GS) which is the velocity of the airplane with respect to the earth along the track angle.

Exercises (684):

1. What defines the clockwise angle from true north to the aircraft centerline?

2. In which direction is the drift when drift angle is greater than true heading?

3. What route is always used to determine distance and time?

4. What does the WIND position indicate?

5. Is the angle displayed in the DSTRK position always the same for a given navigation leg? Explain.

685. State how outputs of the Carousel INS are displayed on the horizontal situation indicator (HSI).

In the previous objective we studied the outputs displayed on the CDU. Some of the outputs are also available as outputs to be displayed on the horizontal situation indicator (HSI). The pilot uses these displays for steering information to fly the aircraft from one point to another.

INS Outputs Displayed on the HSI. See figure 9-15. On the HSI there are several indicators derived from the Carousel INS. These are each displayed as an analog of the indications on the CDU. Let's look first at true heading. True heading (HDG) is displayed on the compass card on the HSI when Carousel INS is selected as the HSI source. The aircraft actual track (TK) is displayed on the Bearing pointer. The angular difference between the compass card and bearing pointer is drift angle (DA). The course command pointer is set in by the pilot and indicate desired track (DSTRK), and the course bar (deflecting left or right of the command pointer) indicates distance cross-track (XTK). The angular difference between the course command pointer (DSTRK) and the bearing pointer (TK) is track angle error (TKE). Of course the TO/FROM arrow is aligned to the desired track to the next waypoint.

Exercises (685):

1. What angle is indicated between the compass card and the bearing pointer?

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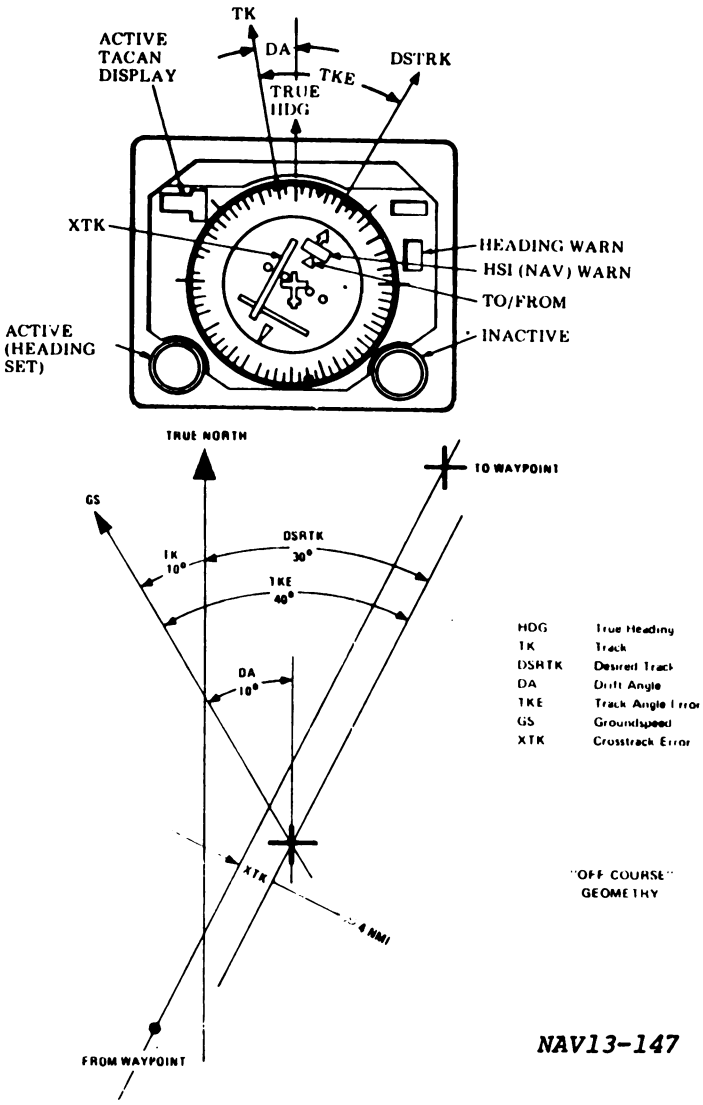

Figure 9–15. Horizontal situation indicator display geometry.

2. What angle is indicated between the course command pointer and the bearing pointer?

3. What angle is displayed by the compass card on the HSI?

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Alignment, Moding, Malfunction Detection, and Maintenance

IN THE PREVIOUS chapter we discussed the general principles and characteristics of the Carousel INS, its theory of operation and its data output displays. In this chapter, we will put some of the principles to use as we see the system align through its submodes and prepare for navigation. We will also see how malfunctions are detected and recorded. Then we will briefly cover the maintenance concept of the carousel INS. Material in this chapter is extracted in part from material released by the Delco Electronics, Division of General Motors.

10-1. Carousel INS Alignment

Alignment of the Carousel INS system takes place when the mode selector switch is set to ALIGN or directly to NAV from OFF or STBY. The alignment is necessary to: align the platform to the desired local level orientation, which places the X and Y instrument input axes in the horizontal; allow the computer to determine the exact orientation of the platform with respect to true north; and allow the computer to determine the effects of any changes in accelerometer loop, gyroscope torquing, or stabilization loop performance since the last time the system was operated.

The alignment is done automatically and is performed in four submodes or computer modes. A numerical code representative of the active submode is displayed on the control/display unit by selecting the DSRTK/STS position.

686. State the characteristics of submode (8) and (9) of the alignment process.

Submode (9). Submode (9) is known as the standby mode because very little alignment takes place. The mode selector switch must be in any position except OFF or ATT to initiate submode (9). During this submode, the gyroscope wheels are started, and the platform temperature is monitored. The gimbals are caged with the platform aligned to the aircraft pitch and roll axes. All instrument warning flags which are controlled by the system, indicate warning. The system remains in this submode for 130 seconds after the fast warmup is complete to ensure the gyroscope wheels have attained synchronous speed.

Submode (8). Submode (8) is the beginning of the Carousel INS alignment sequence. The mode selector cannot be in OFF, STBY, or ATT for this submode to begin. The coarse level submode of alignment levels the X–Y platform with respect to the gravity vector. The aircraft must be stationary during alignment; therefore, the only acceleration sensed by the X and Y accelerometers is a component of gravity acting along the X and Y accelerometer input axes, in the event the platform is out of level. The accelerometer drive electronics produces signals proportional to the amount of acceleration (gravity) sensed by each horizontal accelerometer, and these signals are processed by the gyroscope torquing electronics to provide torque current (positive or negative, as required) to the horizontal gyros, which results in positioning the platform toward the level orientation by driving the gimbals through the pitch and roll stabilization loops. The resultant movement of the platform decreases the accelerometer outputs as the platform drives toward the level orientation. The platform orientation achieved during this submode is close to horizontal, and this mode is complete when the platform drive rate to level is less than 1.5°/min.

If the alignment sequence is begun by setting the mode selector switch to ALIGN from OFF or STBY, a 12.8-second signal is sent to the computer. During the 12.8-second period, the platform is essentially operating in the attitude mode and is operating on battery power to check the capability of the battery to sustain a full system load. The BAT lamp on the control/display unit lights during this period, indicating that battery power is being uscd. A battery failure results in lighting the red BAT lamp on the mode selector unit and causes the system to shut down.

Platform leveling continues with the computer commands in control of the gyroscope torquing until the desired level orientation is achieved.

Minimum time in mode 8 is 51 seconds. The maximum time is 6.8 minutes.

Exercises (686):

1. How long does the system remain in submode (9) after gyros reach operating temperature?

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2. What is the maximum platform drive rate allowed to exit submode (8)?

3. State the minimum and maximum time in mode 8.

687. State the characteristics of submode (7) of the Carousel INS alignment process.

Coarse Azimuth—Submode (7). The purpose of this mode is to determine where true north is with respect to the X and Y instruments and to calculate the approximate latitude where the system is. The latitude approximation will be compared to loaded latitude at entry to computer submode 6 to determine if there is a gross error in loaded present position. The approximation of the angle between the X and Y instruments and true north will be used to apply corrections for earth rate to the platform in the fine ALIGN mode. This initial determination of the angle to true north will then be refined during the fine align.

During this submode, the platform will tilt from the horizontal due to earth rate acting on the X and Y gyros. The output of the X and Y accelerometers due to this tilt will be used to compute local latitude and the angle from Y instruments to true north.

To understand how this is accomplished requires, first, an understanding of the reason for the tilt and, second, how the accelerometer information with the tilt will result in the computation of the latitude angle and the instrument angle to true north.

Platform tilt in submode (7). The effect of earth rate on the levelness of the platform is dependent upon the latitude of the aircraft during alignment and varies from maximum at the equator to zero at the poles. At the equator, the north gyroscope would detect the full earth rate rotation while neither the azimuth nor the east gyroscope would detect any component of earth rate since their input axes are perpendicular to the rotation axis of the earth. Changes in the latitude of this instrument configuration affect the amount of earth rate detected by the north gyroscope in accordance with the *cosine of the latitude*. Since the earth rate component is not compensated for during this mode, the earth rate detected by the north gyroscope results in an output to the stabilization loops causing the platform to be driven in a direction which nulls the north gyroscope signal generator output. As a result, the platform drives out of level about the north axis, and the axis is above horizontal. The net result is that the platform tilts just enough about the north gyroscope input axis so that the east accelerometer will provide an output to the computer which, in turn, will generate a north gyroscope torquing signal that will be used in the gyroscope torquing electronics to generate a north gyroscope torquing current to null the gyroscope output. In a north-slaved instrument configuration then, the platform would exhibit a downward tilt of the west side of the platform. The amount of the platform tilt is dependent upon the latitude of the aircraft during alignment. In Carousel INS, north and east instruments are redesignated Y and X, and the platform is rotated about the Z gyroscope input axis. This means that instead of only one gyroscope detecting earth rate, both the X and Y gyros detect components of earth rate in amount varying as a function of the rotation. However, the resolution of the X and Y gyroscope outputs by the coordinate resolver causes the X–Y platform to tilt the same, due to earth rate, as the north-slaved reference system. The X–Y platform then rotates in a plane tilted about north with the west side low.

True north to XY instrument angle—submode (7). At the entrance to computer mode 7, the Y instruments can be pointed in any direction with respect to true north. For discussion purposes, direction a will be defined as the direction the Y instruments are pointed and direction b for the X instruments.

The azimuth relationship between true north (N) and east (E), the computational a and b, and the x and y instrument input axis are shown in figure 10-1. The angle ωt is the constant X–Y platform rotation rate of 1 RPM with respect to inertial space (ω_z) multiplied by the time (t) in the submode. The angle $\Theta_{yn\ sub\ o}$ is the angle between true north and the y instrument axis at entry of this mode. The computer resolves all velocity data from the accelerometers into the a and b directions so the data internal to the computer can be looked upon as a misaligned north slaved system. After damping or smoothing the data and converting it to an equivalent torque, it is then resolved back through $\omega_z t$ and applied to the respective gyroscope as an electrical torque to the gyroscope float. The float drives off null producing an error signal to the stabilization amplifiers which drive the proper gimbal torque motor causing a rotation about the gyro's input axis resulting in a precessional torque nulling the gyro's output.

Exercises (687):

1. Name the two purposes of the submode (7)?

2. In which direction are the X and Y instruments positioned at the entrance to submode (7)?

3. Why does the platform tilt in submode (7)?

4. Of what use are the X and Y accelerometer outputs when the platform is tilted?

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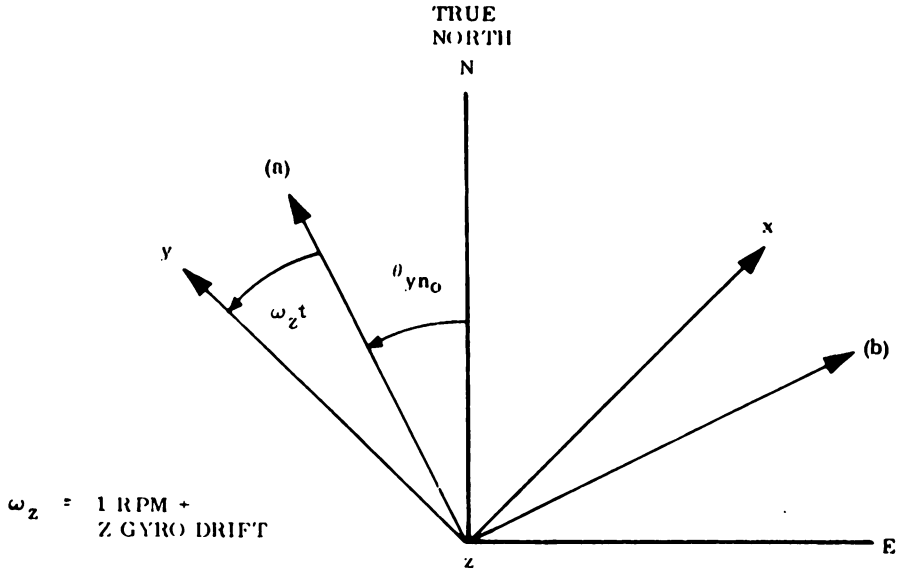

Figure 10–1. Axis relationships during computer submode (7). (Reproduced with permission of the Delco Electronics Division of General Motors)

688. Identify the characteristics of submodes (6) and (5) in the Carousel INS alignment process.

Fine Align—Submode (6). The purpose of this submode is to compute:

- Any change in the horizontal loop performance characteristics, i.e., loop calibration.
- The error in the computation of the angle from the Y instruments to true north. This computation was made in submode 7.

Horizontal Instrument Calibration. At entrance to this computer submode, the computer will torque the gyros to compensate for the earth rate input to the system about true north. The torquing information is derived from the inserted present position latitude.

If the instruments and their associated electronics were perfect devices, the platform would be level at this point and INS would be ready to do its navigation job. All gyros have a drift output, and accelerometers have bias outputs. These are instrument outputs with no inputs. In addition, the associated electronics will also contain errors due to amplifier offsets and aging of components. The computer will compensate for these errors in the instrument loops by torquing the horizontal gyros.

A term that represents the torque value for instrument error outputs is called ω_{SH} and there is one for the X loop and one for the Y loop.

Every time the system is aligned, the change of delta (Δ) in the ω_{SH} values are determined in computer submode 6 on a continuing basis until the navigation (NAV) mode is entered.

The $\Delta\omega_{SH}$ values can be easily determined in submode 6 with a rotating instrument frame by reading the accelerometer outputs at fixed time intervals over one revolution and then dividing the total output over one revolution by the number of times the accelerometers were read in the revolution. The accelerometer output over one revolution is the result of the $\Delta\omega_{SH}$ and any platform tilt due to servoloop errors. The platform tilt will cause a sinusoidal output, the instrument loop changes will be fixed no matter what tilt there is. The accelerometer output due to platform tilt will then resolve to zero over one revolution and the $\Delta\omega_{SH}$ will remain constant.

After I minute in submode 6, a $\Delta\omega_{SH}$ value is calibrated and then 60 seconds later, another value is calculated using data that throws out the first 6 seconds of information and adds on the latest 6 seconds of data. The output is still calculated for 1 minute of data but is a sliding minute. The finer output allows shop personnel to better evaluate the stability of the instrument loop performance.

The accelerometer outputs, in addition to being integrated over one revolution, are also resolved to the north and east frame during horizontal calibration. The platform tilt will not affect the $\Delta\omega_{SH}$ values, as shown previously and, by the same reasoning, the $\Delta\omega_{SH}$ values will affect the accelerometer outputs resolved to the north or east direction.

The computer will torque the platform about north, as described previously. If, however, there is any torquer

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scale factor error, i.e., given input causes specific output of gyro, the platform will not be compensated properly and a tilt about north of the platform will exist which will result in a resolved east accelerometer output. The more the error, the more resolved east accelerometer output.

This computer torquing about true north is only as good as the computer's knowledge of true north. If there is any error in the angle obtained in computer submode 7, the computer's knowledge of true north and east is also in error. If the computer's knowledge of east is incorrect, there will be some earth rate felt about where the computer thinks east is (fig. 10-2).

This earth rate must be compensated for by the resolved north accelerometer output. It can be seen from the illustration that the greater the error in θyn_o, the larger the resolved accelerometer output. This output, when integrated (V_N), is therefore related or representative of the error in θyn_o. This is called the heading error or $\epsilon\gamma$. See figure 10-2.

Vertical Gyroscope Calibration—Submode 5–0. The rotation rate of the XY platform about vertical is equal to one RPM plus the vertical gyroscope output. The vertical gyroscope output is due to its drift characteristics called D_z and the earth rate input.

When the fine align submode is entered, all X and Y accelerometer information is resolved to north and east through this rotation rate. Earth rate is derived from the inserted present position latitude ($\Omega \sin \lambda$) and the drift rate of the Z gyro loop is stored down in computer memory from the last time the INS was operated in the NAV mode.

Any change in the drift characteristics of the Z gyroscope loop will, therefore, result in an error in the accelerometer information resolved to north and east.

Since this is an error in a rate, the resolution of accelerometer information to north and east will rotate at that error rate, i.e., the computer's knowledge of north and east will also drift. The more computed east drifts, the more earth rate is coupled into computed east and the more resolved north accelerometer output is needed to standoff the earth rate input. The resolved north accelerometer information will, therefore, increase the same rate as the error in Z gyroscope drift error, i.e., the time rate of change of computed north velocity is equal to the change in Z gyroscope drift. This error rate is referred to as $\epsilon K\omega$.

The above involves a time rate of change computation and takes a long time, using present computer methods, to arrive at a stabilized value. There is a second method for arriving at the same information which merely involves simple addition, subtraction, and dividing.

The XY resolver which is mounted on the bottom of the inner-roll gimbal has an output that represents the angle from the gyro to the navigation unit's roll axis. This angle will rotate at 1 RPM + Z gyroscope output (fig. 10-3).

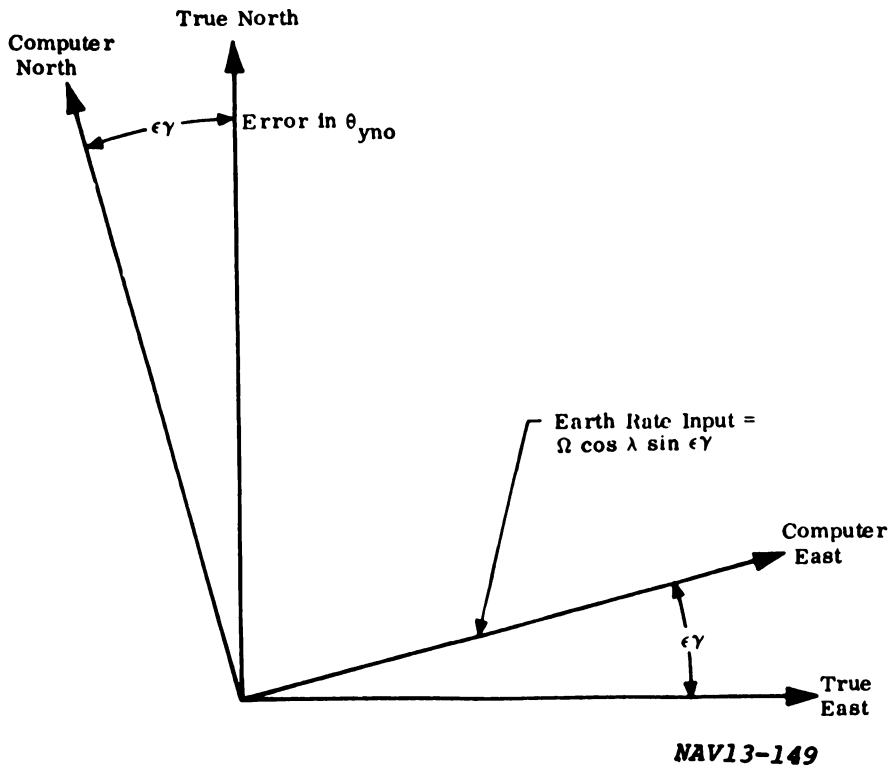

Figure 10–2. Earth rate felt about computer resolved east during align submode (6–0). (Reproduced with permission of the Delco Electronics Division of General Motors)

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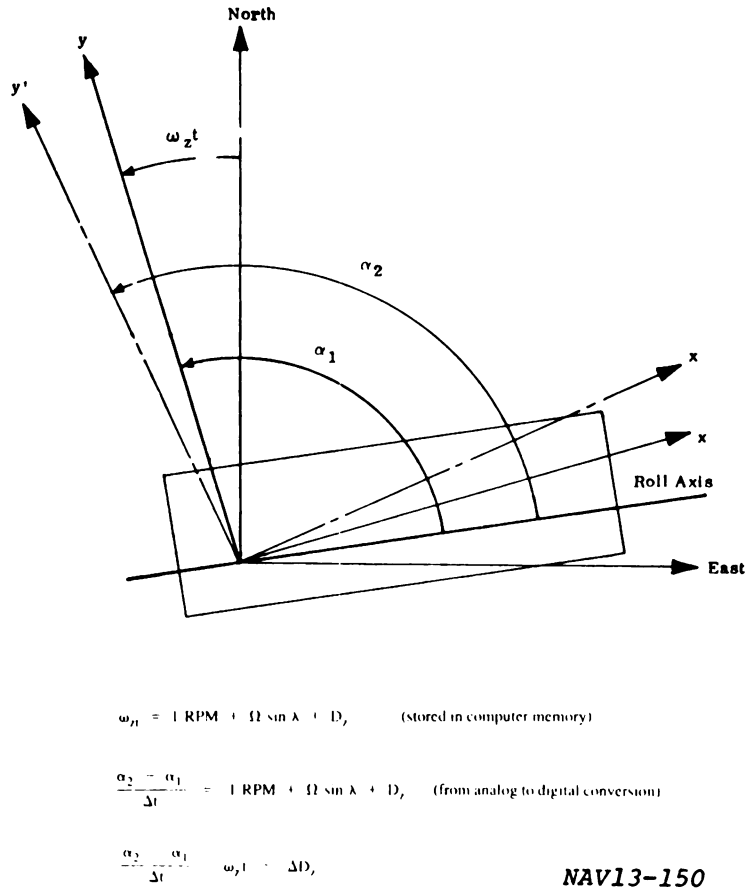

Figure 10–3. Azimuth resolver determination of change in vertical gyroscope drift rate. (Reproduced with permission of the Delco Electronics Division of General Motors)

The XY resolver angle is converted by the analog-to-digital converter every 50 milliseconds. If two consecutive conversions were to be divided by 50 milliseconds, the rotation rate of the XY platform can be calculated.

The computer mathematically subtracts this converted value from that value which was stored in computer memory the last time the INS was operated in the NAV mode. The difference between these two values is equal to Δd_z (fig. 10-3).

Exercises (688):

1. State the purpose of submode (6).

2. How does the computer compensate for errors in the instrument loops?

3. How is the torquing information derived to compensate for earth rate input to system about true north?

4. What is the rate of rotation of the XY platform about vertical?

5. What is the time rate of change of computed north velocity equal to?

10-2. Moding Electronics

In the preceding section we presented the alignment of the Carousel INS. We saw what happens to the platform in each submode of the alignment, how the gyro and accelerometer errors are used to level the platform, and

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final true north. We are now ready to study the moding electronics of the Carousel INS. We have selected the moding electronics because it is a typical circuit operation and because it goes hand in hand with the previous section.

689. Identify the signals present and state their functions during OFF and STBY modes.

NOTE: Refer to figure 10-4 as you study lessons 689 and 690. This figure shows the mode selector switch on the CDU set to ATT mode, but this illustration will be used to explain all the modes of operation of the Carousel INS.

OFF Mode. The INS is not functional when the mode selector on the MSU is in the OFF position. The 24-volt battery unit output power is applied through a diode the to the mode selector to be available at turnon. The 400-Hz excitation and reference voltages from the aircraft systems are applied to the IRU pitch, outer roll, and platform heading synchro and to the DCU digital-to-analog converter when the INS is in the OFF mode.

Standby (STBY) Mode. When the mode selector is set to STANDBY from the OFF position, battery power is applied to a pulser which ensures two relays, K1 and K2, are in the reset position. Then these relays are reset, then power will be applied to the two prime power relays K1′ and K2′. A second contact on the mode selector assures K2′ will be closed by applying battery power to the base of a transistor in its ground circuit. Relay K2′ applies 115V 400-Hz prime power to the AC to DC power converter which outputs 36 VDC unregulated. This 36 VDC then replaces the battery power at the mode selector by backward biasing the diode between the mode selector and the battery. Relay K1′ is not closed until the power regulator is producing +15 VDC. Then the transistor in the ground return circuit of K1′ is enabled. By delaying the energizing of K1′ in this way, large current surges through the contacts of K1′ are eliminated. The battery will now be used if 115V 400 Hz prime power is lost. Any time the 36 VDC unregulated drops below the battery voltage, the diode in that circuit becomes forward biased and the system uses battery power.

When +15 VDC becomes available, it also enables a low-voltage detector circuit which monitors the unregulated 36V from the power converter or 24V from the battery. If this voltage drops below approximately 16V, the transistor in the ground circuit of K1 set side will be turned on causing power to be removed from K1′ and K2′ removing all prime and heater power from the INS, and illuminating the warn lamp on the CDU and the BAT lamp on the MSU.

The contact on the mode selector switch which is closed in STANDBY and ALIGN also applies power to the overtemperature switch through the set side of K2. If an overtemperature is detected, this circuit will be grounded and K2 will be set, removing all power from the INS and applying battery power to the CDU warn lamp.

There are three logic shifters associated with the moding. These logic shifters change the MSU switch logic of 0 VDC and +36 VDC to the +15 VDC and 0 VDC required to operate the mode logic. If a logic shifter has 0 VDC applied, its output will be +15 VDC; if +36 VDC is applied, its output will be 0 VDC.

The computer is started through the use of two signals—one to enable the computer power supply (DC/DC enable) and one to enable the computer PND* (power normal delayed*). As soon as 36 volts becomes available, one input to the gate associated with DC/DC converter enable circuitry goes to a logic 1 and two inputs to the gate associated with PND* are at a logic 1. One of these is from 36V to K1′ and K2′ and the other input is from the low-voltage detect switching transistor. When +15V becomes available, the PND* signal goes to a logic 1 until the rest of the logic inputs are available and the 150-millisecond time delay is complete. With +15 volts available, logic shifter 1 will output +15V (logic 1) provided attitude mode is not selected. This logic 1 will enable the computer power supply after a 20-millisecond delay, enable the control display unit's power supply, and cause PND* to go to a logic 0 after a 100-millisecond delay which allows the compute memory to start operating. If 36 VDC is lost, a low voltage is detected, or attitude mode is selected, PND* will go to a logic 1 to stop the computer before the computer power supply voltages drop.

Application of +15V to the 1.2-kHz inverter enables its operation (starting gyroscope wheels); however, logic shifter 2 output inhibits starting the 130-second time delay and, in this condition, keeps the azimuth stabilization amplifier disabled and causes the other three stabilization amplifiers to cage the gimbals. In addition, logic shifter 2 output (logic 0) also drives a NAND-gate causing it to output a logic 1 (ATT command), which causes timing for the accelerometer circuits to be switched to the frequency divider.

Exercises (689):

1. What voltages are available during OFF mode?

2. What voltage in the moding circuitry takes the system off battery power?

3. What will be the result if K2 is set?

4. What two signals are used to start the computer?

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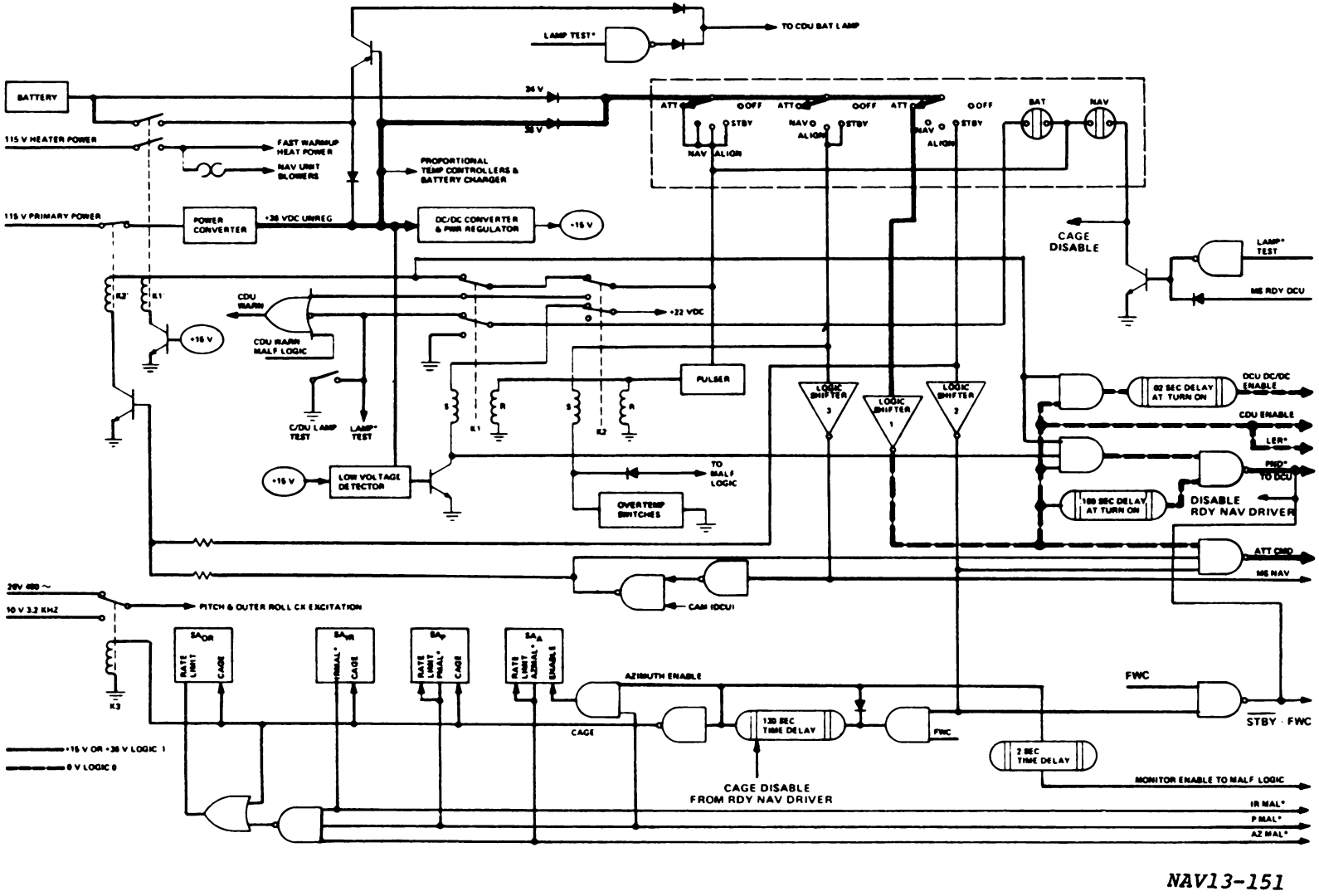

Figure 10–4. Moding electronics. (Reproduced with permission of the Delco Electronics Division of General Motors)

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5. Which signal stops the computer when a low voltage is detected?

690. Identify the signals present and their functions during ALIGN, NAV, and ATT modes.

ALIGN Mode. When ALIGN is selected on the mode selector, logic shifter 2 will output a logic level 1. This output immediately causes the ATT CMD to go to 0. It applies a logic 1 to the AND-gate, driving the 130-second timer, which will start to run as soon as fast warmup complete (FWC) goes to a level 1. At the same time, a NAND-gate provides a logic zero $\overline{\text{STBYFWC}}$ discrete to the computer in order to start a computer-programmed delay.

NOTE: Carousel INS systems have two timers, a 130-second cage timer and a computer-programmed timer, i.e., the time is software dependent. The programmed timer determines when CAM will be issued. Therefore, enabling CAM can be less than, equal to, or greater than 130 seconds.

The computer-programmed timer, which begins at the same time as the cage timer, may be completed first. In such a case, the computer issues a MSRDY discrete. This discrete lights the RDYNAV lamp on the MSU and provides a logic zero cage disable signal to the cage timer. This signal produces the same results that occur on the completion of the cage timer delay.

If the system is downmoded to STBY after the 130-second timer has run out, the output of logic shifter 2 will cause attitude mode gyroscope torquing and accelerometer timing to switch to the frequency divider. The 130-second timer will not recycle, and the gyroscope wheels will remain running and the stabilization loops will remain closed, putting the system in the equivalent of the attitude mode.

In either ALIGN or STANDBY, logic shifter 3 outputs a logic 0. This signal is used to indicate to the computer that NAV has not been selected. The same signal when inverted is applied to a NAND-gate together with a command attitude mode (CAM) discrete from the computer. Prior to the programmed delay time out, CAM is false or at a logic 0 causing this NAND-gate to output a logic 1 keeping K2′ closed. After the programmed delay times out, the computer will issue CAM. The CAM discrete will cause relay power to K2′ to be removed, putting the INS on battery power and it will cause the ATT CMD discrete to be issued as in STANDBY mode. The CAM discrete is issued once for 12.8 seconds during the computer course leveling mode (mode 8). When this occurs, power comes from the battery through the top contact of relay K2′ through a diode to the power regulator. When this diode is forward biased, the BAT lamp on the CDU will be illuminated through the simplified driver circuit shown.

There are no further changes in the moding of the system during the ALIGN mode except internal to the computer.

NAV Mode. The input to logic shifter 3 goes to a 0 level, removing automatic shutdown in case of an overtemperature. The output of logic shifter 3 goes to a logic level 1, indicating to the computer that the mode selector is in the NAV mode. This same discrete inhibits the CAM discrete from causing K2′ to open or the system to go to the attitude mode.

Attitude (ATT) Mode. When ATT is selected on the mode selector, the output of logic shifter 1 will go to a logic 0: ATT CMD will become true, causing ATT mode timing and torquing. The CDU ENABLE discrete will go false, shutting off the control display unit power supply and the computer will be shut down through the removal of PND* and the computer DC/DC enable and a low erection rate (LER) discrete will be issued to the gyroscope torquing electronics.

Exercises (690):

1. When does the 130-second timer start?

2. What signal lights the RDY NAV light on the MSU?

3. What signal out of logic shifter 0 indicates to the computer that NAV has not been selected?

4. Which command generates the 12.8-second battery check?

5. In NAV mode what signal inhibits the CAM discrete?

6. Which signals are removed to shut down the computer in ATT mode?

10-3. Malfunction Detection and Maintenance

In the preceding chater and sections, we have seen basically how the Carousel INS works. It is a very reliable system but does occasionally require maintenance, if nothing other than a fresh program. The system has built-in test capability which automatically runs tests to confirm the system's operational capability. Malfunctions are stored for future recall. Now let's look at malfunction detection and recall.

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691. Identify identifications of malfunctions.

The INS includes a computer which employs an extensive range of self-tests to monitor system integrity. Most system malfunctions are detected by these tests. All malfunctions detected by these tests, except those which do not affect system performance, are announced by lighting of the CDU WARN indicator. All malfunctions detected by self-tests are identified by setting the CDU data selector to DSRTK/STS and reading the CDU right-hand data display. Some malfunctions for which INS is responsible are not detected. These malfunctions are reported as abnormal indications on indicators and instruments of interfacing systems or simply as navigation inaccuracies.

Action Codes and Malfunction Codes. After a flight on which malfunctions have occurred, some malfunctions will be present in the form of malfunction codes as soon as the system is turned back on. When the CDU data selector is set to DSRTK/STS (fig. 9-9), the right-hand data display indicates one of the five action codes (01 thru 05) in the second and third digit positions from the left. More than one malfunction can be present for display, and the action code indicates the priority of the most serious malfunction present. The 01 code indicates highest priority. **Reading Malfunction Codes and Action Codes.** There is a code to identify every malfunction detected by INS self-tests. By pressing the TEST switch on the CDU, the action code is replaced by a malfunction code. The lowest malfunction code is 12 and the highest is 63. Each malfunction code must be recorded. Each actuation of the TEST switch will present a different malfunction code until all existing malfunctions are identified. (They are presented in numerical order.) After the last malfunction code is presented, an action code may reappear upon next actuation of the TEST switch. If no action code appears (blank display), the malfunctions were intermittent and no longer exist or were residual malfunctions from the last operation. If a new action code appears, two possible situations exist, a higher priority action code indicates a new, more serious malfunction is present, or a lower priority action code indicates a more serious malfunction that was intermittent has disappeared, and the action code for the next most serious malfunction has taken its place.

Malfunction Code Recorded During Flight. All malfunctions, even intermittent ones, which occur during a flight are recorded in the INU and may be reviewed on the ground. However, the data is erased if the system is turned on after shutdown and allowed to sequence to alignment status 7. To prevent this, select the standby mode (STBY) when first turning on the system and record all of the malfunction codes stored in the INU as the first step in the general troubleshooting procedure.

Malfunction Codes. Malfunction codes are related to actual operation of INS. Checks of the following operational characteristics are made: noise levels in the basic electronics, temperature, internally generated commands, reasonableness of computer calculations and operations, INS outputs, digital-to-analog conversion, movement of the aircraft during alignment, correct insertion of present position,, gyro and accelerometer degradation and INS inputs. Malfunctions are of varying degrees of seriousness, ranging from danger to the equipment to degraded performance, to invalid outputs, to mere advisories. The applicable aircraft technical orders or the field maintenance tech orders list all malfunctions by action code, in order of importance, and provide a brief description of each and the modes in which they are generated.

Exercises (691):

1. Which malfunctions do not light the CDU WARN light?

2. Where are action codes displayed on the CDU?

3. Which action code is the most serious?

4. What is indicated if no action code appears after all malfunction codes have been displayed?

10-4. Troubleshooting and Programming Carousel INS

We have seen how malfunction codes are recorded and recalled by the operator. When you have an action code and a malfunction code, what do you do next? The next few paragraphs will tell you what to do.

692. State the general troubleshooting procedures for the Carousel INS.

Troubleshooting Procedures. When you suspect that the Carousel INS is causing a malfunction, turn on the Carousel INS and perform a malfunction check. If no malfunction codes are present, observe indications on the CDU and MSU and visually record any malfunction symptoms. If there are malfunction codes, refer to the list of malfunction symptoms to determine the appropriate action tree to use to troubleshoot the malfunction. Figure 10-5 shows a sample of a list of malfunction symptoms. If a new malfunction code appears while you are in the process of troubleshooting, complete the troubleshooting in progress before starting on the new action tree, unless the new malfunction has a higher priority than the one being investigated. Determine the appropriate action tree to use for troubleshooting action. (Figure 10-6 shows a sample action tree.)

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MALFUNCTION SYMPTOM	ACTION TREE NO.
CONTROL DISPLAY UNIT (CDU)	
CDU data displays blank and MSU BAT and CDU WARN indicators not on	AT-1
CDU data displays blank with CDU WARN and MSU BAT indicators on - Low voltage shutdown	AT-2
CDU data displays blank with only the CDU WARN indicator on - Over-temperature shutdown	AT-3
CDU data displays frozen or un-intelligible data	AT-4
CDU light, data display or display segment failure during CDU light test	AT-5
TEST/AUTO-MAN switch on CDU inoperative	AT-6
Malfunction code 12 - Invalid TAS	AT-7
CDU DISPLAYED MALFUNCTION CODES	
Malfunction codes 13, 14, 32, 59, or 63 - INU related failures	AT-8
Malfunction codes 15, 45, or 60 - INU alignment failure	AT-9
Malfunction code 16 - Invalid pitch and roll input	AT-10
Malfunction code 17 - Invalid magnetic heading from N-1 compass system	AT-11
Malfunction codes 20 through 25 - Synchro 26 vac excitation failure	AT-12

MALFUNCTION SYMPTOM	ACTION TREE NO.
Malfunction code 20 - Computed true airspeed failure	AT-13
Malfunction code 21 - True heading No. 2 failure	AT-14
Malfunction code 22 - Drift angle plus track angle error No. 1 failure	AT-15
Malfunction code 23 - Drift angle failure	AT-16
Malfunction code 24 - Steering failure	AT-17
Malfunction code 25 - True heading No. 1 failure	AT-18
Malfunction code 26 - Pilot HSI course deviation indicator failure	AT-19
Malfunction code 31, 42, or 62 - INU platform error	AT-20
Malfunction code 33, 34, 35, or 36 - NAV unit failure	AT-21
Malfunction code 37 or 38 - NAV unit platform overtemperature	AT-22
Malfunction code 46 - INU installed with incorrect program	AT-23
Malfunction code 49 - Navigation inaccuracy 1. Loaded present position greater than 33nm from last displayed position 2. Manual position update greater than 33nm 3. Radar position update rejected	AT-24

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Figure 10-5. INS troubleshooting index of malfunctions symptoms.

Isolate the malfunctioning equipment in accordance with the action tree.

Replace the responsible unit using the appropriate removal and installation procedures as directed by the action tree. Reactivate the Carousel INS and ensure that the malfunction has been cleared. If not, troubleshoot using an appropriate action tree.

Exercises (692):

1. If there are no malfunction codes present, is the system serviceable? Explain.
2. If malfunction code 45 is displayed on the CDU, where do you go next?
3. Which action tree should you use to troubleshoot malfunction code 45?

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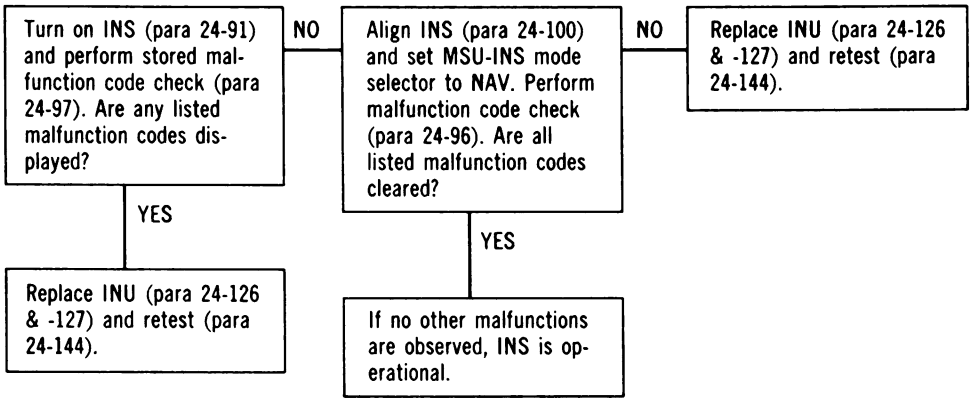
AT-8. MALFUNCTION CODES 13, 14, 32, 59, OR 63 – INU RELATED FAILURES (ON AIRPLANES INCORPORATING T.O. 1C-135-1067).


Turn on INS (para 24-91) and perform stored malfunction code check (para 24-97). Are any listed malfunction codes displayed?
NO
Align INS (para 24-100) and set MSU-INS mode selector to NAV. Perform malfunction code check (para 24-96). Are all listed malfunction codes cleared?
NO
Replace INU (para 24-126 & -127) and retest (para 24-144).
YES
Replace INU (para 24-126 & -127) and retest (para 24-144).
YES
If no other malfunctions are observed, INS is operational.

AT-8A. MALFUNCTION CODES 13, 14, 32, 59, OR 63 – INU RELATED FAILURES (ON AIRPLANES INCORPORATING T.O. 1C-135-1114).

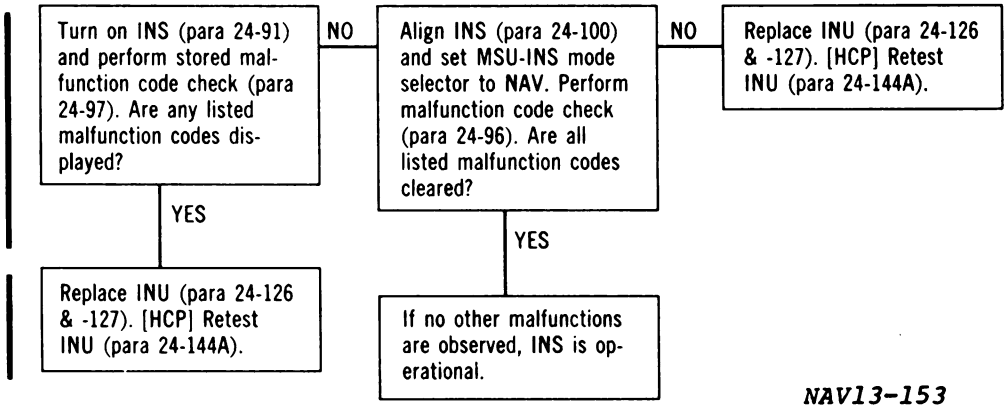

Turn on INS (para 24-91) and perform stored malfunction code check (para 24-97). Are any listed malfunction codes displayed?
NO
Align INS (para 24-100) and set MSU-INS mode selector to NAV. Perform malfunction code check (para 24-96). Are all listed malfunction codes cleared?
NO
Replace INU (para 24-126 & -127). [HCP] Retest INU (para 24-144A).
YES
Replace INU (para 24-126 & -127). [HCP] Retest INU (para 24-144A).
YES
If no other malfunctions are observed, INS is operational.
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Figure 10–6. Action tree.

693. Describe the procedure for loading a program into the Carousel INS.

The Carousel INS has had its malfunctions analyzed. The system has been troubleshot and repaired, perhaps by replacement of the INU. The only thing left is to load the INU with the appropriate program. (The program number used depends on the type aircraft on which the INU is installed. The program is loaded on a cassette such as you use in your home stereo.) To load a program in the INU, we use the program load unit (PLU) (fig. 10-7).

Setup. Refer to figure 10-7 for location of the controls used as we go through the setup, load, and verify procedures. First, connect the PLU to the buffer box (not shown) and the buffer box to the NAV unit, then plug the PLU into prime power. Proceed as follows:

- PLU power switch—ON.
- MSU mode switch—STDY.
- Insert cassette (with correct program).
- Press—RESET (tape light OFF).
- Press—REWIND (tape rewinds, stops and tape light ON).
- Press—RESET (tape light OFF).

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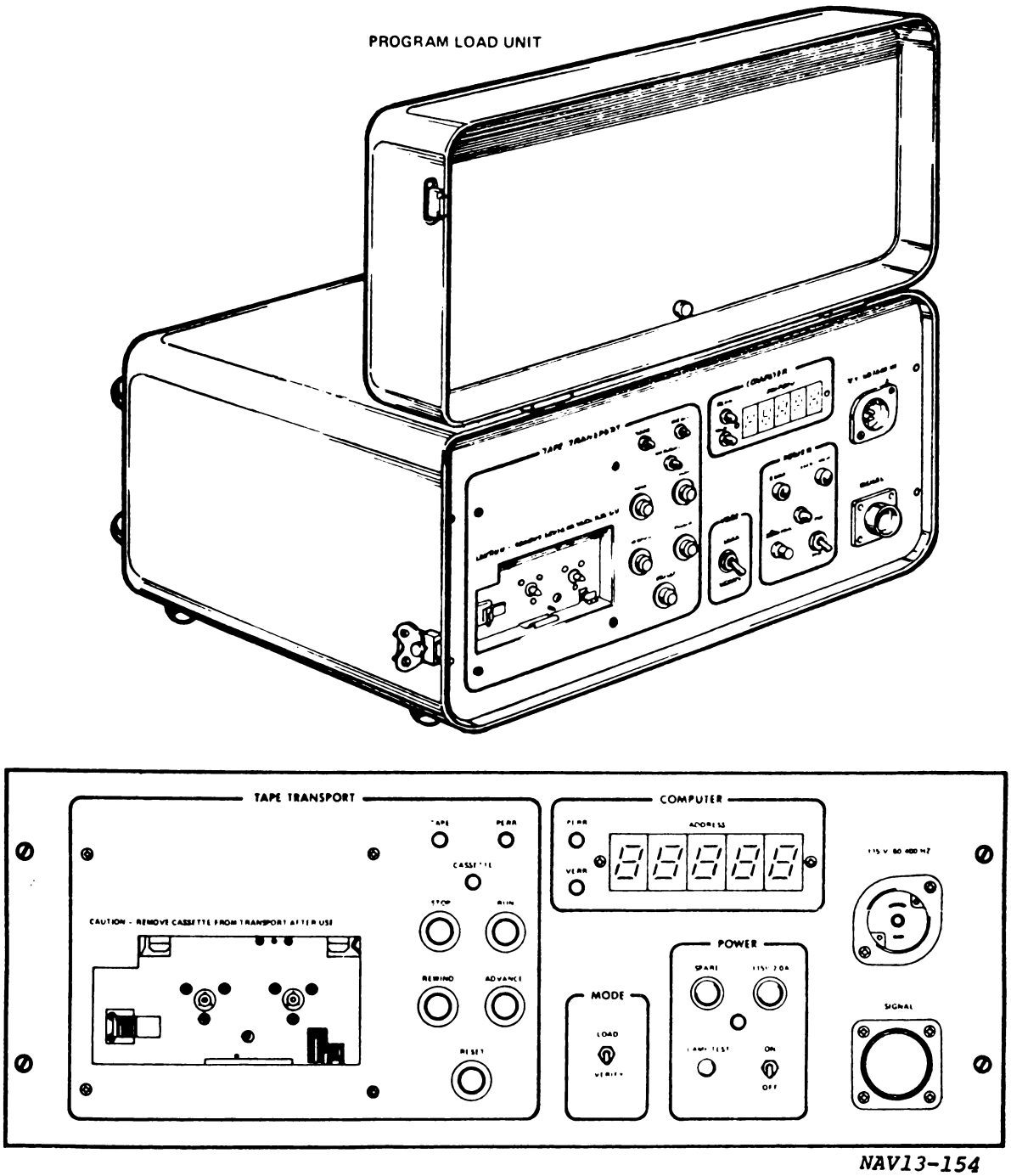

Figure 10–7. Program load unit.

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Load Procedures. Now we are ready for the load procedure. To load the program proceed as follows:

- Check cassette label to ensure proper program.
- Mode switch—LOAD.
- Press—ADVANCE (tape drive, stops, start address displayed).
- Press—Run (tape runs, stops at end of program).

Verify Procedures. Now we need to verify that the tape has been properly loaded. Your tape will have a second program identical to the first for the verification procedure. To verify the program proceed as follows:

- Mode switch—VERIFY.
- Press—ADVANCE (when tape stops, start address displayed).
- Press—RUN (tape runs, stops at end of program. Tape will stop when an error is detected and show a PERR for parity error).
- After the RUN is completed, press—REWIND (when tape stops, tape light ON) and press—RESET (tape light OUT).

To check the program number loaded in the Carousel INS, do the look routine as listed in the appropriate aircraft tech order and call up address 2776. The CDU should display: 13670003, if the cassette loaded is labeled P/N 7891367003.

Exercises (693):

1. Why would you use the RESET button on the PLU?

2. Where should the MSU mode switch be set when you are loading a program?

3. Why should you check the program number?

4. How many programs are loaded on the cassette? Why?

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Answers for Exercises

CHAPTER 1

Reference:

600 - 1. S.
600 - 2. A.
600 - 3. A.
600 - 4. S.

601 - 1. Three axes: east-west, north-south, and vertical.
601 - 2. Pitch, roll, azimuth, and velocity.

602 - 1. "X" axis; east.
602 - 2. "Y" axis; north.
602 - 3. Coriolis; centripetal.
602 - 4. Coriolis; centripetal.
602 - 5. Z.
602 - 6. Local vertical.

603 - 1. Velocity is rate of change of distance. Acceleration is rate of change of velocity.
603 - 2. You can determine velocity by integrating acceleration.
603 - 3. Differentiating velocity yields acceleration.

604 - 1. T.
604 - 2. F. Change "angular" to "linear."
604 - 3. T.
604 - 4. F. Change "only if motor 1 is turning" to "even if motor 1 stops turning."
604 - 5. F. Change "acceleration" to "velocity."
604 - 6. T.
604 - 7. T.
604 - 8. F. Change "narrow" to "wide."
604 - 9. T.

605 - 1. Three accelerometers are required to pinpoint a position in space.
605 - 2. Their sense axis must be kept oriented to the proper direction by mounting them on a platform oriented to local vertical, despite pitch and roll gyrations of the aircraft.
605 - 3. The primary purpose of the inertially derived true morth signal in an inertial navigation system is for azimuth stabilization of the platform.
605 - 4. The gyroscope furnishes signals to the inertial stable platform for horizontal stabilization.
605 - 5. By making a servoloop in which an inertially derived true north signal controls the aximuth.
605 - 6. By a system of gimbals positioned by signals from gyroscopes.

CHAPTER 2

606 - 1. b.
606 - 2. a.
606 - 3. a.
606 - 4. c.

607 - 1. Gyroscopic inertia is that characteristic of a spinning body to resist a change in its orientation.
607 - 2. Angular momentum is the cause of gyroscopic inertia.
607 - 3. The mass of the gyro, the distance of the center of mass from spin axis, and the speed of rotation.
607 - 4. M, c.
ω, a.
R, b.

608 - 1. F. The force must be applied perpendicularly.
608 - 2. T.
608 - 3. T.
608 - 4. F.
608 - 5. F. The maximum precession due to earth rotation is 15° per hour.
608 - 6. T.
608 - 7. T.
608 - 8. T.
608 - 9. F. The gyro is sensitive to torque about the axes perpendicular to the spin axes.
608 - 10. F. When the spin vector and torque vector are aligned there is no further precession.

609 - 1. One.
609 - 2. True north.
609 - 3. Hortizontal.

610 - 1. The added mass gives the rotor greater radius and hence greater angular momentum.
610 - 2. The motor is the major part of a gyro.
610 - 3. A precision frequency and voltage are used to spin the gyro motor to maintain the angular velocity which keeps the angular momentum exact and constant.
610 - 4. The pickoff coils obtain an AC voltage from the excitation coils.
610 - 5. Winding the pickoff coils 180° out of phase provides a means of detecting the direction of case movement.
610 - 6. The 90° displacement between the torquing and pickoff components is necessary because a gyro precesses about an axis which is 90° away from the applied force.
610 - 7. The gyro motor and housing.

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610 - 8. Displacement of the gyro rotor by unwanted torque caused by friction or imperfections in the gyro.
610 - 9. An AC voltage.
610 - 10. Two gyros.

CHAPTER 3

611 - 1. Law of inertia—a body at rest tends to remain at rest, whereas a body in motion tends to stay in motion. Law of momentum—when a force acts upon a body, it changes the momentum of that body. Law of reaction—every action is resisted by an equal and opposite reaction.
611 - 2. This is an example of the law of reaction.

612 - 1. Average speed $= \frac{300 \text{ meters}}{15 \text{ min}} = 20 \frac{\text{meters or}}{\text{min}}$

$1{,}200 \frac{\text{meters}}{\text{hour}}$

612 - 2. a. $\bar{V} = \frac{\frac{48 \text{ km}}{(\text{hour})^2} \times \frac{\text{hour}}{12}}{2} = 2 \frac{\text{km}}{\text{hour}}$

b. $D = \bar{V} t$
$= 2 \text{ km} \times \text{hour}/12 = 1/6 \text{ km}$

613 - 1. The smallest acceleration is called the threshold of sensitivity.

613 - 2. This accelerometer is called *linear*.
613 - 3. These accelerometers are linear only near their null position.
613 - 4. Its ability to discern small increments of change.
613 - 5. Because spring constants are different for different amounts of acceleration and if a pendulum is used gravity acts on it when displaced from the center of the arc.
613 - 6. The extent from least to the maximum acceleration that the accelerometer can sense.

614 - 1. The adjustable weight permits the precise balancing of the pendulum.
614 - 2. The main purpose of filling the case assembly with fluorolube is to float the pendulum, thereby removing all weight from the jewel bearings; also, to decrease friction.
614 - 3. The 5-kHz oscillator generates a 5-kHz reference signal for the excitation of the coils in the case assembly plus an input to the restoring amplifier and demodulator.
614 - 4. The relationship is directly proportional.
614 - 5. The signal out of the pickoff coils determines the direction of current flow.
614 - 6. The voltage represents a desired number of g's.
614 - 7. It is necessary to calculate the value of the scale factor resistors for each accelerometer because the amount of current necessary to null each individual instrument varies.
614 - 8. The amount of bias current necessary to null an accelerometer varies with each instrument because of inconsistency in the mass, an eccentric pivot, or unbalanced spring rate of the instrument.
614 - 9. The quadrature resistor compensates for a 90° phase shift between the excitation coil and the pickoff coil.
614 - 10. Cover assembly.
614 - 11. To compensate for thermal expansion of the fluorolube.
614 - 12. The temperature compensating resistor.
614 - 13. Two volts per g of acceleration.

CHAPTER 4

615 - 1. Three axes about which an aircraft moves are the longitudinal, lateral, and yaw (or vertical) axes.
615 - 2. This is the longitudinal axis.
615 - 3. The roll angle is measured in the vertical plane and has a maximum value of $\pm$ 180°.
615 - 4. The aircraft is flying straight up.
615 - 5. If the yaw angle of an aircraft is 180°, the aircraft is flying south.

616 - 1. Two 2-degree-of-freedom gyroscopes are needed to establish the three orthogonal axes of our frame of reference.
616 - 2. The minimum required is two.
616 - 3. Their sensitive axes are mutually perpendicular.
616 - 4. The X and Y accelerometers.

617 - 1. Gimbal.
617 - 2. First alignment phase is to local vertical and the second is to true north.
617 - 3. Accelerometers.
617 - 4. Trigonometric.
617 - 5. Accelerometers.
617 - 6. By applying computed torque rates to the gyroscopes to compensate for earth and transport rates.

618 - 1. Ωy (horizontal component of earth rate) $= \Omega \cos \phi$
$= (15.04188°) (\cos 0°)$
$= (15.04188°) (1) = 15.04188°$
The gyroscopes must be torqued at 15.04188° per hour about the north-south axis.

Ωz (vertical component of earth rate) $= \Omega \sin \phi$
$= (15.04188°) (\sin 0°) = 0°$
The gyroscopes will not need to be torqued about the vertical axis.

618 - 2. $\omega y = \Omega \cos \phi + \frac{Vx}{R}$

$= (0.26253) (\cos 0°) + \frac{0 \text{ mph}}{3{,}959 \text{ m}}$

$= 0.26253$ radians/hour or 15.04188°/hour

$\omega x = \frac{Vy}{R} = \frac{395.9 \text{ mph}}{3{,}959 \text{ m}} = 0.1$ radians/hour or 18°/hour

$\omega z = \Omega \sin \phi + \frac{Vx}{R} \tan \phi$

$= (0.26253) (\sin 0°) + \frac{0 \text{ mph}}{3{,}959 \text{ m}}$

$= 0$ radians $+ 0$
The gyroscopes will not need to be torqued about the vertical axis.

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618 - 3. The rate of rotation about the vertical axis would decrease.

$$\downarrow \omega z = \frac{Vy}{\uparrow Rz}$$

618 - 4. The east-west axis. $\omega x = \frac{Vy}{R}$

618 - 5. The vertical axis of transport rate.
$\omega z = \Omega \sin \phi + \frac{Vx}{R} \tan \phi$

618 - 6. The east-west velocity. $\omega y = \frac{Vx}{R}$

619 - 1. Two gyros are used.
619 - 2. They are connected one on top of the other in a dumbbell configuration, both spin axes are in a horizontal plane but perpendicular to each other.
619 - 3. Azimuth, inner roll, pitch, and outer roll.
619 - 4. The azimuth gimbal has 360° movement, the inner roll has ± 18° movement, and the pitch has 360° movement.

620 - 1. b.
620 - 2. a.
620 - 3. c.
620 - 4. d.
620 - 5. d.
620 - 6. e.
620 - 7. g.
620 - 8. i.
620 - 9. j.
620 - 10. h.

CHAPTER 5

621 - 1. b.
621 - 2. a.
621 - 3. a.
621 - 4. a.
621 - 5. d.
621 - 6. c.
621 - 7. c.
621 - 8. a.

622 - 1. CEP is 5.5 NM/hr in rapid alignment.
622 - 2. Drift accuracy of the gyros is 0.01° per hour.

623 - 1. c.
623 - 2. f.
623 - 3. a.
623 - 4. b.
623 - 5. e.
623 - 6. g.
623 - 7. d.
623 - 8. 2.25 minutes
623 - 9. The Vx integrator longitude rate.
623 - 10. Platform, navigation computer, OSDU, relay panel.

624 - 1. A and B phases are used for this purpose.
624 - 2. The primary uses of the regulated +30 VDC are for transistor bias, to develop the precision + 10 VDC, to provide excitation to the 3-kHz frequency generator, and for the primary power control circuits.
624 - 3. 5.8 VAC 400 Hz is used as antibacklash voltage for servos in the INS.
624 - 4. We use A, B, and C phases of the aircraft power to generate the voltage which energizes A3K22.
624 - 5. We use B and C phases of the aircraft power to generate excitation voltage for the vibrators.
624 - 6. The input to the second frequency divider located in the computer supply is 1.5 kHz and its output is 375 Hz.
624 - 7. The sustaining voltages applied to the gyro spin motors in Af, Gc, and NAV are Aϕ, Bϕ, and Cϕ; 90 VAC 375 Hz.
624 - 8. The run up voltages for the gyro spin motors in Ac are Aϕ, Bϕ, and Cϕ; and 140 VAC 400 Hz.
624 - 9. Outputs of the OSDU power supply are 13 VAC, AB ϕ, 400 Hz.

625 - 1. Velocity in the east-west direction.
625 - 2. Aircraft ground velocity.
625 - 3. Velocity in the north-south direction.
625 - 4. Angle of longitude.
625 - 5. Rate of rotation of the earth.
625 - 6. An apparent force at right angles to the direction of motion of an object moving over a rotating reference.
625 - 7. Aircraft heading with respect to magnetic north.
625 - 8. Inertial altitude.

626 - 1. The purpose of standby is to bring the environmental circuits to operating temperatures.
626 - 2. The purpose of coarse-align is to rapidly align the gimbals with approximately true north and the attitude of the aircraft.
626 - 3. The purpose of fine align is to make small and exact adjustments to the level attitude of the gimbals.
626 - 4. The purpose of gyrocompass is to make small and exact adjustments to the azimuth attitude of the stable element (azimuth gimbal).
626 - 5. The purpose of navigate is the operating mode of the INS. All useful output signals are derived in this mode.

627 - 1. Heading memory; BATH.
627 - 2. Heading memory; BATH.

628 - 1. b.
628 - 2. c.
628 - 3. a.
628 - 4. a.
628 - 5. d.

629 - 1. The temperature control assembly (3A23).
629 - 2. Thermistors.
629 - 3. The proper temperature has not been attained.

630 - 1. In Ac, when BCX4 has no output, the outer roll gimbal is aligned approximately to the attitude of the aircraft.
630 - 2. The pitch servoamplifier assembly, 3A3, provides the drive voltage for BM5 and BM6 in Ac.

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630 - 3. During Ac, 15 VAC 4.5-kHz excitation is applied to the inner roll control transmitter.
630 - 4. In Ac, the output of the inner roll servoamplifier, 3A3, is zero when BCX2 has no output.
630 - 5. In Ac, a 4.5-kHz signal is produced when the angular position of the stable element and the true heading servoshaft in the OSDU are not in coincidence.
630 - 6. The output is zero.

631 - 1. The accelerometers control the leveling of the platform.
631 - 2. Proper orientation is maintained by slaving the stable elements to the gyros.
631 - 3. The output polarity of the X-accelerometer restoring amplifier 3A7 depends on the phase difference between the 4.5-kHz reference signal and the accelerometer error signal.
631 - 4. They are applied to the Y-torquer coil of the lower gyro YZ1.
631 - 5. The function of BXC2 during Af is to drive the outer roll servomotor until the outer roll gimbal and the inner roll gimbal are aligned.
631 - 6. During Af, the sensed output of the Y-accelerometers causes BM5 and BM6 to drive.
631 - 7. During Af, the output of 3A18 is ωz. This signal is applied to the Z1-axis torquer coil of the YZ1 gyro.
631 - 8. The torque applied to the XZ2 torquer in Af is such that it will cause the Z2-axis to align to the Z1-axis.

632 - 1. Y-accelerometer.
632 - 2. 3A24R18C, the secant potentiometer.
632 - 3. To the YZ 1 lower gyro.
632 - 4. Zero.

633 - 1. The true tangential velocity of the vehicle is the basis for the various corrections used in the navigate mode.
633 - 2. The signal is the drive signal for the Vx integrator motor.
633 - 3. The -Vx signal is corrected for the equatorial radius of the earth in a resistive network at the input to assembly 3A6.
633 - 4. The converging longitude lines at high altitudes cause this.
633 - 5. The longitude integrator obtains the $\pm \cos \phi$ input from a cosine potentiometer which is located on the latitude integrator shaft assembly.
633 - 6. The output is proportional to the velocity input to the loop.
633 - 7. The output, $\frac{-Vx}{R1}$, from the second summing amplifier of the 3A6 assembly represents craft rate.
633 - 8. The output, $-\Omega \cos \phi$, of the 3A16 assembly represents earth rate.
633 - 9. It provides $\pm$ Vy signals that correspond to the aircraft velocity along the Y-axis.
633 - 10. The function of resistive network R2 at the input of summing amplifier 3A12 is to correct craft rate for the polar radius of the earth.
633 - 11. It precesses until the sum of the Y-accelerometer signal and the Y-accelerometer bias voltage is zero.
633 - 12. The Z1 torquing loop provides the current.
633 - 13. They are computed in the latitude integrator.
633 - 14. It is caged by a signal developed by the caging amplifier on assembly 3A2.
633 - 15. Centripetal potentiometer R3 provides the centripetal correction $\frac{Vx^2}{R1} \tan \phi$.
633 - 16. Centripetal correction $\frac{Vx^2}{R1} \tan \phi$ is applied to the Vy channel.
633 - 17. In the navigate mode, $\frac{-Vx^2}{R1} \tan \phi$ and $\frac{+Vx}{R1} \tan \phi$ are the inputs to centripetal potentiometer R4.
633 - 18. The function of R18A in the navigate mode is to provide the Y-channel with coriolis correction, 2 Vx sin ϕ.
633 - 19. 2 Vy sin ϕ is the coriolis correction for the Vx channel.
633 - 20. An air data computer provides barometric altitude for the INS.
633 - 21. They drive the displacement integrators.

CHAPTER 6

634 - 1. The required voltage for the INS heaters is 115 VAC, 400 Hz, phases A and B.
634 - 2. In the STBY mode, relay 3A23K22 energizes and provides ground for bridge rectifier 3A25A1CR4, thereby completing the circuit to energize power relays 3A25A1K3 and 3A25A1K4.
634 - 3. Relay 3A25A1K3 controls the C ϕ voltage to the power supply transformers.
634 - 4. The purpose of the interlock circuit in the INS is to insure that all the connectors have been properly mated and seated before power is applied to the applicable units.
634 - 5. In the ALIGN mode, relay K27 provides ground for relays 3A25A1K1 and 3A25A1K2, thereby applying 140 VAC 400 Hz to the gyro spin motors.
634 - 6. The 140-VAC 400-Hz, 3-phase power is applied to the gyro spin motors for 60 seconds.
634 - 7. K27 must be deenergized.
634 - 8. When K28 deenergizes, it causes K22 to deenergize, thereby deenergizing the entire INS except for the heater power to the environmental control circuits.
634 - 9. Relays 3A25A1K3 and 3A25A1K4 are energized in the STBY, ALIGN and NAV modes.
634 - 10. Components A1R4, A1R12, A1C16, and A1C17 on assembly 3A25 form an RC network which delays the DC voltage to the solenoid of relay A25A1K8 for approximately 250 milliseconds.
634 - 11. With the symptoms provided, it is apparent that relay 3A25A1K8 is inoperative and not providing ground through contacts 3 and 4 for A1CR4.
634 - 12. Components A1R3 and A1CR2 rectify the 115-VAC, C ϕ voltage to a DC voltage that is used to energize A1K5 and A1K6.

635 - 1. The 4.5-kHz power supply provides excitation for the gyros, accelerometers, and synchros.
635 - 2. Transformer T6 provides voltage for the gyro spin motors during Ac.
635 - 3. The difference between the input to T2 and T3 is that one signal is phase-shifted by 90° from the other.
635 - 4. The 1.5-kHz input is generated by a 3-kHz tuning-fork type generator.

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636 - 1. The regulated ± 30-VDC supply, within assemblies 3A21 and 3A25, provides the voltage used as transistor bias in the INS.
636 - 2. This voltage is used as the control voltage for the regulated +30 VDC output of Q7.
636 - 3. The precision +10 VDC and -10 VDC are used as references for the gyros, accelerometers, and computing devices.
636 - 4. The function of 3A22A2CR1 is to regulate the voltage at the junction of 3A22A1R26 and 3A22A1R25.
636 - 5. If series regulator 3A24A1Q9 does not drop the +30 VDC to exactly +10 VDC, an error signal is applied to a summing amplifier. This compensates the regulator output for the error.
636 - 6. These outputs are used as transistor bias and reference voltages.

637 - 1. 3A23A1K1 and 3A25A1K4 must be energized.
637 - 2. The output of the temperature-sensing amplifier which gates the ambient heater control circuits determines current flow through the heaters.
637 - 3. This output controls the air valve through BM9.
637 - 4. Thermostats S1 and S2 control the component oven temperature.
637 - 5. 165°.
637 - 6. It determines the amount of current flow through the ambient heaters.

638 - 1. R1 of B2 on foldout 6.
638 - 2. Control windings of BM1 and BM2.
638 - 3. XZ2 pickoff coils.
638 - 4. Z1 pickoff coil.

639 - 1. Stator windings of BCX3 on foldout 7.
639 - 2. Y-gyro pickoff coil.
639 - 3. Stator S1.
639 - 4. When the output of the secondary of the lower gyro Y pickoff coil is zero.

640 - 1. Stator windings of BCX2 on foldout 8.
640 - 2. The upper gyro X-pickoff coil senses this misalignment.
640 - 3. Aircraft attitude.
640 - 4. To R2 of azimuth resolver BR1.

641 - 1. The linear channel controls the outer roll gimbal servodrive during normal operation of the system.
641 - 2. A nonlinear gain network is required.
641 - 3. During Af and NAV, the output of BCX4 represents the roll angle of the aircraft. This signal is used in associated avionics.
641 - 4. In the NAV mode, the output of 3A8 is applied to 3A1 to vary its gain relative to the pitch angle of the aircraft.
641 - 5. The rate channel.
641 - 6. To the linear channel of 3A1 assembly.

642 - 1. The purpose of 3A22A2C1 is to provide a series of positive and negative pulses.
642 - 2. A1L1 is designed to act as an arc suppressor.

643 - 1. Accelerometer bias is applied to assembly 3A4 to compensate for the inherent accelerometer error.
643 - 2. In the NAV mode, A26C2 is in the circuit. This causes DC amplifier 3A4 to operate as a low-gain amplifier.
643 - 3. In the NAV mode, the function of K1 is to remove the degenerative feedback signal of assembly 3A4.
643 - 4. The signal from the wiper of 3A24R1B represents east-west velocity.
643 - 5. The output of summing amplifier 3A12A, -Vy, is applied to summing amplifier 3A12B to obtain +Vy.
643 - 6. Motor 3A24B4 drives the wiper arm of S3, R2B, and R2A that provide Vy information.

644 - 1. The normally open contacts.
644 - 2. In ALIGN, the only input to assembly 3A15 is present position data from the latitude demodulator.
644 - 3. The rotor output is proportional to the velocity input to the loop.
644 - 4. At the junction of resistors 3A22A2R6 and 3A22A1R4.
644 - 5. Present position longitude.

645 - 1. The polarity of the DC signal from Q4 is determined by the phase difference between the 4.5-kHz reference signal and the input from AC amplifiers Q1-Q3.
645 - 2. Whenever displacement of the element occurs.
645 - 3. Accelerometer pickoff error signal and 4.5 kHz refer signal.
645 - 4. To the accelerometer torquing coil.

646 - 1. The Y-accelerometer bias is used to bias DC amplifier assembly 3A10.
646 - 2. There is an input to the X-torquing coil until the sum of the Y-accelerometer signal and the Y-accelerometer bias voltage is zero.
646 - 3. The function of 3A26K7 is to change the amount of Y-accelerometer bias applied to assembly 3A10.
646 - 4. During ALIGN when the sum of the Ax signal and the X-accelerometer bias voltage is zero, the input to the Y-torquing coil is zero.
646 - 5. The function of K1 is to control the feedback loop of assembly 3A4.

647 - 1. The Ay sec ϕ signal, earth rate, transport velocity, and Z-axis gyro bias are summed and used to torque the Z1 torquer.
647 - 2. This voltage is applied when K21 is energized.
647 - 3. During NAV, the function of the Z1 torquing loop is to provide a current which is proportional to the combination of earth rate, transport velocity, and Z-axis gyro bias.
647 - 4. The input to the AC amplifier in assembly 3A2 is the sum of both Z1 and Z2 pickoff coil outputs.
647 - 5. Earth rate, transport velocity, and Z-axis gyro bias.
647 - 6. By the addition of feedback resistor A28R76 through the contacts of relay K16.

CHAPTER 7

648 - 1. Resistor A1R7 is the bias-adjust resistor for A1Q1.
648 - 2. The function of A1C1 is to keep the base of A1Q1A referenced to AC ground.

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648 - 3. The forward bias increases.
648 - 4. When transistor A1Q5 is forward biased to saturation, its collector is at ground potential.
648 - 5. Current flow through A1R14 forward biases A1Q6.
648 - 6. CR1 and CR2 switch when the gyro heater's power is maximum.
648 - 7. A1Q1A's bias increases.
648 - 8. The maximum power that reaches the upper gyro heaters is 70 percent of the available power.
648 - 9. The gyro temperature detector initiates the 50-second time delay when the correct gyro temperature is reached.
648 - 10. The instant A2CR14 and A2CR15 becomes back biased, A2C12 starts to charge to the positive supply voltage.
648 - 11. A2Q25 is forward biased when the voltage drop across A2R65 is sufficient to break down zener diode A2CR17.
648 - 12. The charging current of A2C12 back biases A2Q22.
648 - 13. The sawtooth voltage from the relaxation oscillator is used as bias on the bases of A1Q3, A1Q9, and A1Q15.
648 - 14. The function of A1CR10 and A1CR11 is to rectify the output of T6.
648 - 15. A decrease in current flow through A1R51 lowers the forward bias on A1Q20.
648 - 16. The ambient thermister DC bias on A1Q3, A1Q9, and A1Q15.
648 - 17. Standby, align, and navigate.
648 - 18. It maintains a constant potential between the emitter of A1Q19 and the base of A1Q20.
648 - 19. Platform heater power control signal.
648 - 20. A2R56.
648 - 21. It changes from negative to positive.
648 - 22. Because the operating temperature of the upper and lower gyros differ from the ambient operating temperature.
648 - 23. During the manufacturer's test.
648 - 24. (1) Supply power required to bring the gyros, accelerometers, and platform ambient heaters to operating temperature.
(2) Maintain the correct temperatures.
(3) Initiate a 50-second time delay when gyro operating temperature is reached.

649 - 1. Closed.
649 - 2. Both thermostats are closed.

650 - 1. Base bias voltage for Q11 and Q12 is obtained by the voltage developed across diodes CR7 and CR8.
650 - 2. The purpose of Q9, Q10, and T3 is to form a phase inverter to drive compound-connected push-pull output transistors Q11, Q12, Q13, and Q14.

651 - 1. The power-interrupt circuit insures that relays K1 and A4K1 remain deenergized for approximately 250 milliseconds after power is turned on.
651 - 2. The RC network consisting of A1R2 connected in parallel with the back resistance of A1CR1 and A1C1, provides the 250-millisecond delay.

652 - 1. Ground for A1CR4 is provided through NC contacts of A1K8.
652 - 2. If either of the voltages mentioned exceeds the limit set in assembly 3A21, A1K7 energizes A1K8. This, in turn, deenergizes the INS power supplies by causing relays A1K3 and A1K4 to deenergize.
652 - 3. Filtering of the +45-VDC unregulated output is accomplished by A1L1-A, A2C4, and C1.
652 - 4. Diodes A2CR7 through A2CR12 in foldout 20 form a 3-phase, full-wave rectifier for the T6 output and provide the DC voltage necessary to produce the -30 VDC.
652 - 5. The output of the +28-VDC unfiltered power supply is used as collector voltage for the transistors in the final stages of the various INS servoamplifiers.
652 - 6. The functions of R2 and R3 in the STBY +28-VDC power supply are to reduce the rectified output voltage from A1CR5 through A1CR7 to +28 VDC.
652 - 7. The output of the 12.6-VAC 400-Hz power supply is used to provide a modulating signal for DC levels in the various amplifier assemblies.
652 - 8. When the INS control is switched to align or navigate.
652 - 9. Ground is removed from point 8 of A1K7 by the power supply disable circuit.
652 - 10. Relay A1K7 will be deenergized intermittently by the power supply disable circuit but the INS power supply disable relay A1K8 will not energize to shut off the power supply due to the short time the voltage is out of tolerance.
652 - 11. 12.6 VAC, 400 Hz.
+28 VDC, unfiltered and 5.8 VAC, 400 Hz, ϕ C.
652 - 12. 5 amps.
652 - 13. They make up a half-wave rectifier for the 115 VAC, 400 Hz, 3-phase power.
652 - 14. In the computer to energize K22.

653 - 1. The +30 VDC regulator in foldout 21 uses +45 VDC to provide a +30-VDC $\pm$ .15-volts precision voltage.
653 - 2. Resistor R8 is a variable resistor that is used to adjust the regulator circuit to provide +30-VDC $\pm$ .15-volts regulated output.
653 - 3. This increase causes the base potential of Q1 to decrease.
653 - 4. Resistor R2 and diode CR1 maintain the base bias of Q3 fixed at +9.3 VDC.
653 - 5. The regulator circuit in foldout 21 is protected from a short-circuit overload by CR2, R6, R8, and R9.
653 - 6. During normal operation, the signal at the collector of Q15 in foldout 21 is a 10-volt, peak-to-peak signal.
653 - 7. C11 in foldout 21 is a filter capacitor which filters out any high-frequency components of the input signal.
653 - 8. Input to the flip-flop in foldout 21 is a 3-kHz signal, and the output is a 1.5-kHz square wave.
653 - 9. The switching of the flip-flop (Q17 and Q18, foldout 21) is determined by the RC time constant represented by the coupling capacitor and resistor from the collector of one transistor to the base of the other transistor.
653 - 10. The function of Q19 in foldout 21 is to act as a buffer between the flip-flop and the 4.5-kHz resonant tank circuit, consisting of C18 and L1.
653 - 11. The function of A1R1 and A1R2 is to provide a voltage drop that is used to alternately bias Q1 and Q2 on and off.
653 - 12. The 3A25 is deenergized by removing the ground for relay A1K7.

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653 - 13. CR10, CR11, R27 on foldout 21 form a gate circuit that is used to sense any change in the +28 VDC filtered or unfiltered voltages.

654 - 1. When Q15 in foldout 22 is not conducting, its collector voltage is +30 VDC.
654 - 2. The output frequency of Q15 in foldout 22 is half of the input frequency because Q15 conducts only during alternate negative input pulses.
654 - 3. The transistors provide an overall gain of less than one.
654 - 4. L1 and C2.
654 - 5. 90 VAC.
654 - 6. During the dynamic test to assure balanced input.

655 - 1. The function of R12 and CR15 in foldout 23 is to establish the emitter voltage of Q5.
655 - 2. Diodes CR8 and CR9 in foldout 23 function as amplitude-limiting diodes.
655 - 3. The time constant of R2 and C1 controls the flash rate of the align light.
655 - 4. When any voltage deviates from a predetermined value, the go/no-go circuit initiates the system failure signal.
655 - 5. Capacitor C17 (foldout 23) is a coupling capacitor that couples the output signal from the collector of Q7 to the base of Q11.
655 - 6. The system failure signal is produced when Q13 is cut off.
655 - 7. The pitch angle detector output is proportional to the pitch synchro output.
655 - 8. The AC load in the emitter circuit of Q9 in foldout 23 is T3.
655 - 9. The signal amplitude increases.
655 - 10. The 60 second time delay.
655 - 11. By application of 28 VDC to the collector of Q14 during align.

656 - 1. Q13, Q15, and Q17 control Q19 when the input is is less than +10 VDC.
656 - 2. When the +28-VDC input to Q4 (foldout 19) is removed, A1CR2, A1CR3, and A1R3 provide a discharge path for C1.
656 - 3. Transistors Q7 and Q8 form a differential amplifier.
656 - 4. Q9 conducts when its base potential becomes negative with respect to its emitter.
656 - 5. Diode A4CR1 (foldout 19) provides a rapid discharge path for C2 and C3.
656 - 6. CR2 will break down causing Q4, Q5, and Q6 to conduct.
656 - 7. Zener diodes CR10 limits input voltage to a maximum ±11 VDC.
656 - 8. Q19 will be conducting.

657 - 1. Resistors A1R4 and A1R5 in figure 7-2 form a voltage divider that sets the emitter voltage of A1Q3.
657 - 2. Diodes A1CR4 and A1CR5 block +28 VDC from the time delay circuit during the ALIGN mode.
657 - 3. A1R1 and A1C1.
657 - 4. Capacitor C1 is discharged through A1CR8.

658 - 1. To amplify the weak signal before transporting it any distance.

659 - 1. These inputs are the 4.5-kHz outputs from the platform resolver.
659 - 2. The phase difference between the reference signal at its base and the error signal at its emitter.
659 - 3. C7 is the integral gain capacitor.
659 - 4. Integral gain capacitor C7 (foldout 24) is bypassed by external relay action during the Ac submode.

660 - 1. The aircraft pitch angle determines the amount of attenuation.
660 - 2. The DC input from the pitch angle detector causes the impedance of the variable attenuator network in foldout 25 to vary.
660 - 3. The collector voltage is proportional to the emitter voltage.
660 - 4. During ALIGN, the signal at the junction of R50 C19 in foldout 25 is a DC signal which was modulated (chopped) at a 400-Hz rate.
660 - 5. A decrease in current through the primary of T1 (foldout 25) causes an increase in current through Q16.
660 - 6. The output of Q9 is the same polarity and phase as the output of Q5.
660 - 7. Cascade.
660 - 8. At the emitter of Q13.
660 - 9. Q17 and Q18.

661 - 1. The collector loads for Q2 and Q3 in foldout 18 are the halves of the primary winding of T2.
661 - 2. The purpose of T1, zener diodes CR1 and CR4, and CR2 and CR3 is to form a full-wave demodulator.

662 - 1. The true-heading servoamplifier in foldout 18 utilizes the heading error signal and the true-heading servotachometer output to create the drive signal for the true-heading servomotor.
662 - 2. Heading error signal and true heading servotachometer output.
662 - 3. By the voltage drop across CR9 and CR10.

663 - 1. During INS alignment, C7 on foldout 26 is short circuited to provide a DC output that responds more rapidly to the input signal for the circuit.
663 - 2. When diode bridge CR3 in foldout 26 is conducting, the voltage at pin B of T2 is developed across filter-input capacitor C17.
663 - 3. At the emitter of Q8.
663 - 4. Current flow through Q11 will increase.
663 - 5. The primary winding of T2.
663 - 6. Through the Z2 gyro torquer coil.

664 - 1. The function of the accelerometer-restoring amplifier is to supply current which maintains a null between the acceleration torque and the magnetic restoring torque.
664 - 2. Through the collector of Q3 through R8 and R3 to the base of Q1.
664 - 3. It provides temperature stability for the Z accelerometer torque output.
664 - 4. Preamplifier, demodulator, and DC output amplifier.
664 - 5. By the phase difference between the reference voltage on the base and the error signal on the emitter.

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665 - 1. The DC input is converted to AC and amplified because AC amplification results in greater amplifier stability for low-level input signals.
665 - 2. The AC gain of A1Q1 and A1Q2 in foldout 28 is established by feedback from the emitter of A1Q2 through A1R6 to the base of A1Q1.
665 - 3. Chopper G1 in foldout 28 chops the AC output signal of A1Q3 to ground, which restores the signal to a DC voltage.
665 - 4. The output of Q1 (foldout 28) is the sum of the amplified signal from the AC amplifier section and the high-frequency components of the unamplified input signal.
665 - 5. Diodes CR6 and CR8 in foldout 28 establish and maintain temperature-compensated DC forward bias at the base of Q4 and Q5.
665 - 6. By diode CR3 conducting.
665 - 7. Because of the bypass action in the emitter A1Q2.
665 - 8. Degenerative.

666 - 1. Capacitor A3C5 and resistor A3R12 (foldout 29) from the collector to the base of A3Q3 provide degenerative feedback to prevent high-frequency oscillations.
666 - 2. Zener diode A1CR1 (foldout 29), in the base circuit of Q1, establishes the maximum negative voltage that can be applied to the base of Q1.
666 - 3. This transformer provides degenerative feedback to the emitter of Q1 for frequency stability.
666 - 4. Two, one navigate and one align.
666 - 5. To prevent high-frequency oscillation.
666 - 6. To prevent low-level signal voltages from driving the amplifier.
666 - 7. Zener diode A3CR3.

667 - 1. The resistive and capacitive decoupling network in the collector circuit of the two transistors (foldout 30) prevents AC variations from affecting the DC operating supply voltage.
667 - 2. The function of C5 in foldout 30 is to filter any high frequency noise generated by chopper G1.
667 - 3. To obtain greater amplifier stability for low-level input.
667 - 4. To produce a DC voltage proportional to the output of AC at Q1.
667 - 5. By current limiting resistors R21, R22, R23, and R26.

668 - 1. This is done in the NAV mode.
668 - 2. The demodulator (A5Q14) output is used.
668 - 3. A4K4 selects this excitation for R17.
668 - 4. $\Omega \cos \phi$ and $-\Omega \cos \phi$.
668 - 5. It acts as an arc suppressor for capacitance tachometer S4.
668 - 6. By a cam on the altitude shaft.

CHAPTER 8

669 - 1. A resistance and continuity check should be performed prior to applying power to the platform so as not to damage the platform or test equipment.
669 - 2. To perform platform resistance checks in a minimum amount of time, use of a resistance/continuity check box is recommended.
669 - 3. When the integrity of the test set is suspected, a self-test should be performed.
669 - 4. Receptacles must be covered with protective caps to protect the pins from being bent and to keep them free from dust, grease, and oil.

670 - 1. You must wait 30 minutes for the accelerometers to cool down; otherwise, applying to a cold gyro and hot accelerometer may damage an accelerometer.
670 - 2. The maximum area temperature should not exceed 80°F.
670 - 3. The best method is substitution of the suspected assembly.
670 - 4. If the roll displays are incorrect, computer tests 1, 2, 3, 17, and 18 should be performed.
670 - 5. By performing tests relating to the circuits most likely to have caused the malfunction.
670 - 6. Perform test numbers 1 and 3.

671 - 1. No. They can be connected separately, although the gyro bias potentiometers are on the OSDU; the bias is determined by adjusting dials on the test set and transferring these readings to the OSDU dials.
671 - 2. The accuracy of the Sanborn Recorder.
671 - 3. They must be centered on the chart and individual deflection angles calibrated.
671 - 4. Bias is determined during platform tests by adjusting dials on the Sanborn Recorder that are similar to the gyro bias potentiometers on the OSDU.

CHAPTER 9

672 – 1. Gyros, accelerometers, motors, synchros, and resolvers.
672 – 2. 2: X–Y platform and Z platform.
672 – 3. In the vertical.

673 – 1. Timing, memory, arithmetic unit/instruction processing unit, input/output unit.
673 – 2. Timing unit.
673 – 3. The data word is twice as long as the instruction word.
673 – 4. Discrete, binary, binary coded decimal, or analog.

674 – 1. In the IRUE.
674 – 2. 6.144 MHz.
674 – 3. C0, C1, and C2.
674 – 4. C0.
674 – 5. The timing generator.

675 – 1. 8,192 words, each 13 bits in length.
675 – 2. 3000_8.
675 – 3. X-axis drive, Y-axis drive, inhibit, and sense.
675 – 4. Allows the power supply convertor to stabilize before turning on the memory.
675 – 5. Allows operations already in progress to be completed before complete shut down.

676 – 1. Instruction word.
676 – 2. 12.
676 – 3. Operand code and address code.
676 – 4. Its memory location.
676 – 5. 24.
676 – 6. The most significant digit (MSD).

677 – 1. Arithmetic unit.
677 – 2. Instruction processing unit.
677 – 3. Control display unit.

678 – 1. Converting information and matching computer speed to input/output.
678 – 2. Programmed input/output section and the automatic input/output section.
678 – 3. Priority (gateman) logic.

679 – 1. Control and display unit.
679 – 2. ATT.

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679 – 3. 30 minutes.

680 – 1. Free-azimuth system.
680 – 2. The horizontal instrument set.
680 – 3. 1 rpm.
680 – 4. The aircraft's latitude and velocity.

681 – 1. Uncompensated drift, torque scale factor instability, and misalignment of input axis.
681 – 2. Electrical or mechanical torques which exist in the gyro independent of any applied precession torques.
681 – 3. A small part of the angular rate occurring about another axis.
681 – 4. Less critical.
681 – 5. Will cause the platform to be positioned out of the desired level position. As a result the accelerometer will sense false acceleration.

682 – 1. 1 rpm plus or minus the effective rotation of the inertially stable Z platform.
682 – 2. Azimuth stabilization loop.
682 – 3. Modulated relative to earth coordinates and not modulated.
682 – 4. It will be reversed when the platform rotates through 180°, to produce only small position errors in the reference frame.
682 – 5. Alignment benefits.
682 – 6. That the platform is off level.
682 – 7. One step.

683 – 1. OFF, STBY, ALIGN, NAV, ATT.
683 – 2. The system is aligned and ready to navigate.
683 – 3. That the system has gone on battery power and the battery is not sufficiently charged.

684 – 1. True heading.
684 – 2. Right drift.
684 – 3. Great circle.
684 – 4. Wind speed in knots and wind direction.
684 – 5. No. The angle displayed will vary depending on the point on the great circle track.

685 – 1. Drift angle.
685 – 2. Track angle error.
685 – 3. True heading.

CHAPTER 10

686 – 1. 130 seconds.
686 – 2. 1.5°/min.
686 – 3. 51 seconds to 6.8 minutes.

687 – 1. To determine where true north is and to calculate the approximate latitude.
687 – 2. Any direction with respect to true north.
687 – 3. From the earth rate acting on the X and Y gyros.
687 – 4. They are used to compute local latitude and the angle from Y instruments to true north.

688 – 1. Loop calibration and compute the error in the true north computation done in mode 7.
688 – 2. By torquing the horizontal gyros.
688 – 3. It is derived from the inserted present position latitude.
688 – 4. 1 rpm plus the vertical gyroscope output.
688 – 5. The change in the Z gyroscope drift.

689 – 1. 24 VDC and 400 Hz excitation and reference voltages.
689 – 2. 36 VDC unregulated.
689 – 3. All power will be removed from the INS and the CDU warn light will be lit.
689 – 4. DC/DC enable and PND*.
689 – 5. PND*.

690 – 1. After FWC (fast warmup complete) is over.
690 – 2. MSRDY.
690 – 3. A logic 0.
690 – 4. CAM.
690 – 5. The logic 1 out of logic shifter 3.
690 – 6. PND* and DC/DC enable.

691 – 1. Those which do not affect system performance.
691 – 2. On the right-hand display.
691 – 3. Action code 01.
691 – 4. The malfunction codes were intermittent.

692 – 1. Not necessarily. There could be external malfunctions such as the MSU, CDU, or battery which do not show up as malfunction codes.
692 – 2. To the list of malfunction symptoms.
692 – 3. Action tree 9.

693 – 1. To turn out the TAPE light.
693 – 2. STBY.
693 – 3. Different aircraft require different program numbers.
693 – 4. 2. So you can verify the program without rewinding the cassette.

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